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USACERL INTERIM REPORT M-90/11
April 1990
Corrosion Mitigation in Civil Works Projects

AD-A222 011

Improved Ceramic Anode Designs and Installation for Lock and Dam Gates

by
Ashok Kumar
Mark D. Armstrong

The objective of this research was to design and demonstrate improved ceramic anode configurations and installation for lock and dam gates.

Two new ceramic anode configurations were developed for use in impressed current cathodic protection systems. Flat disk ceramic anodes and rod ceramic anodes have been installed at two demonstration sites.

It is recommended that monitoring continue at the demonstration sites for 2 years and anode placement be studied for optimum current distribution.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1990

3. REPORT TYPE AND DATES COVERED
Interim

4. TITLE AND SUBTITLE
Improved Ceramic Anode Designs and Installation for Lock and Dam Gates

5. FUNDING NUMBERS
CWIS 31204

6. AUTHOR(S)
Ashok Kumar
Mark D. Armstrong

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratory
P.O. Box 4005
Champaign, IL 61824-4005

8. PERFORMING ORGANIZATION REPORT NUMBER
USACERL-IR-M-90/11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Directorate of Civil Works
Headquarters, U.S. Army Corps of Engineers
20 Massachusettes Avenue, NW.
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
ceramic materials
anodes
locks (waterways)
dams

15. NUMBER OF PAGES
73

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

FOREWORD

This study was conducted for the Directorate of Civil Works, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under CWIS 31204 (Corrosion Mitigation in Civil Works Projects). The HQUSACE Technical Monitor was Mr. John Gilson, CEEC-EE.

The research was conducted by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. R. Quattrone is Chief of USACERL-EM. The Technical Editor was Gloria J. Wienke, USACERL Information Management Office.

MAJ (P) Thomas Sydelko is Commander of USACERL, and Dr. L. R. Shaffer is Director.

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IMPROVED CERAMIC ANODE DESIGNS AND INSTALLATION FOR LOCK AND DAM GATES

1 INTRODUCTION

Background

Cathodic protection is an electrochemical technique wherein cathodes on a corroding structure are polarized to the open-circuit potentials of anodes. This technique can effectively mitigate both underground and underwater corrosion.[1] The U.S. Army Corps of Engineers has used cathodic protection since 1950 to extend the effective life of paint coatings on immersed steel surfaces of navigation lock gates on the Mississippi River.[2]

Cathodic protection can be accomplished using two techniques: (1) the sacrificial/galvanic anode system where the driving voltage for cathodic current flow results from the natural potential difference between the anode material and the structure to be protected and (2) the impressed current system where the driving voltage for cathodic current flow (from auxiliary, usually relatively inert anodes) results from an external power supply such as a rectifier.

To solve some of the problems related to manufacturing and installing graphite and silicon-iron anodes, the U.S. Army Construction Engineering Research Laboratory (USACERL) has been investigating various properties and designs for ceramic anodes since 1983.[3] Ceramic anodes consist of a thin metal oxide coating, which functions as the reactive material, deposited on a relatively inexpensive metallic substrate which is passive under anodic conditions. The anode's electrical connection is factory-fabricated and contains a series of watertight seals.

USACERL Technical Report M-87/03 discussed new ceramic materials and configurations which reduce anode substrate machining costs and minimize exposure to damaging ice and debris. Ceramic anode configurations most suitable for water application were not commercially available.

Objective

The objective of this research was to design and demonstrate improved ceramic anode configurations and installation for lock and dam gates.

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[1] F. Kearney, *Corrosion Control in Civil Works,* Technical Report (TR) M-222/ADA045184 (U.S. Army Construction Engineering Research Laboratory [USACERL], August 1977).

[2] A. Kumar, R. Lampo, and F. Kearney, *Cathodic Protection of Civil Works Structures,* TR M-276/ADA080057 (USACERL, December 1979).

[3] E. G. Segan and A. Kumar, *Preliminary Investigation of Ceramic-Coated Anodes for Cathodic Protection,* TR M-333/ADA133440 (USACERL, August 1983); J. H. Boy, et al., *Improved Ceramic Anodes for Corrosion Protection,* TR M-85/02/ADA149492 (USACERL, November 1984); J. H. Boy, A. Kumar, and M. Blyth, *Development of New Materials and Design Configurations to Improve Ceramic Anode Performance,* TR M-87/03/ADA176315 (USACERL, December 1986).

Approach

Based on literature and general field information, factors important in cathodic protection design were refined and general design considerations were developed. New ceramic anode configurations were developed and installed at two demonstration sites.

Mode of Technology Transfer

This study will impact the proposed Corps of Engineers Guide Specification on cathodic protection of lock gates.

2 DESIGN CONSIDERATIONS FOR HYDRAULIC STRUCTURES

Designing a cathodic protection system to mitigate corrosion of immersed steel in hydraulic structures requires consideration of the following factors:

1. Corrosivity of the water,

2. Coating selection and condition, and

3. Advantages and limitations of the two cathodic protection systems.

Evaluation of these factors helps to determine the number of anodes needed.

Corrosivity of the Water

The corrosivity of the water is the single most important criterion for designing a cathodic protection system. The corrosivity of water depends on its resistivity, pH, oxygen concentration, hardness, and other factors such as sulphate-reducing bacteria. Saltwater has a low resistivity which makes the water more corrosive. A small decrease in pH (e.g., from 6 to 4) can make water more acidic and extremely corrosive. Oxygen concentration cells increase the corrosion rate of steel in water. Oxygen-poor areas are anodic to oxygen-rich areas and can increase the corrosion rate. Another significant factor is water hardness. Hard water has a tendency to deposit a carbonate scale on the steel surface. This scale acts like a coating and protects the steel. Therefore, soft water is more corrosive to steel structures than hard water.

Coating Selection and Condition

Protective coatings are a major means of controlling the effects of corrosion. Selecting a proper coating depends a great deal on the exposures to which it will be subjected. Water corrosivity, turbulent and/or abrasive flow, type of substrate, and materials and labor costs all influence coating selection.

In general, vinyl coatings perform well in quiet fresh water; they usually have a lifetime of 20 or more years. However, vinyl coating life is considerably decreased by poor surface preparation and thin or uneven coverage. In addition, damage caused by turbulent water knocking debris against the coating can reduce the coating life. In brackish water (resistivity less than 2,500 ohm-cm), the performance of vinyl coatings is marginal and applying epoxies for added chemical resistance is necessary.

Seawater, which contains approximately 3.5 percent salt and a fair amount of organic biomass, is a severe environment. Even the best coatings (e.g., coal tar epoxy) may last only 5 to 10 years in seawater. The splash zone is a particular problem area. However, zinc-rich coatings, which eliminate or reduce rust undercutting, can be of some value in the splash zone area.[4]

[4] A. Kumar and D. Whittmer, "Coatings and Cathodic Protection of Pilings in Saltwater: Results of Five Year Exposure," *Materials Performance*, Vol 18 (1979), p 9.

Although coatings are a major form of corrosion control, no coating is perfect. All coatings have at least some porosity to water and chloride ions through pinholes and other mechanical defects in the film. Considering these defects and certain types of severe exposure, using cathodic protection in conjunction with the coating system is warranted. Even in medium to high resistivity water (4,000 to 10,000 ohm-cm), cathodic protection must be considered for areas that are mostly or completely inaccessible for painting because pH levels, oxygen concentration cells, and/or sulfate-reducing bacteria could still create a corrosive environment. Cathodic protection can even be an economic alternative to coatings for mitigating corrosion of submerged seawater structures.

Investigations have revealed that cathodic protection increases the life of the coating (and thus, the structure) by preventing undercutting at damaged areas.[5] When designing a cathodic protection system, the engineer must predict what the condition of the coating is likely to be after 15 to 20 years of service. Distribution of the cathodic protection current is greatly improved by even a relatively poor coating. During cathodic protection, polarization is accompanied by the deposition of a carbonate coating, which also improves distribution of the cathodic protection current.

A bare plate of steel in fresh water requires approximately 22 mA/m^2 (square meter) for cathodic protection in quiet water.[6] If the velocity of the water increases to 1.22 m/s, then the current required increases to 215 mA/m^2. The current required for cathodic protection varies linearly with the square root of the water's velocity. A new painted steel surface requires only about 2.2 mA/m^2 for cathodic protection in moving water; older water-logged vinyl coatings require 11mA/m^2. It should be noted that current requirements for cathodic protection must take into account the eventual deterioration and degradation of the painted coating, and therefore be considerably higher than that for a relatively new coating. In addition, current requirements are based on the premise that the cathodic protection system, and therefore all included anodes, should have a 20 year life expectancy.

Cathodic Protection Systems

Sacrificial Anode Cathodic Protection

Advantages of a sacrificial anode cathodic protection system include:

- No external power required.
- Anodes are easy to install.
- Anodes can be readily added and replaced in areas accessible to divers.
- Minimum of cathodic interference (stray current corrosion).
- Minimum maintenance.
- Uniform distribution of the current.

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[5] A. Kumar, R. Lampo, and F. Kearney.
[6] A. Kumar, R. Lampo, and F. Kearney.

• Effic·· . use of the protective current.

Limitations associated with sacrificial anode systems include:

• Limited driving voltages (i.e , a maximum of about 0.9 volt [V]).

• Lower and limited current outputs.

• Poorly coated structures require many anodes and their associated weight.

• Can be ineffective in high-resistivity environments.

• Cost of dewatering to replace anodes.

Because of the electrochemical/physical characteristics of sacrificial anodes (Table 1), many anodes are required for long life expectancy cathodic protection of certain Civil Works structures (especially uncoated or poorly coated miter and sector gates). The presence of ice and/or debris makes it imperative that these anodes be protected from mechanical damage.

Table 1

Characteristics of Commonly Used Sacrificial Anodes

Anode	Efficiency, Percent*	Density, g/cm^3	Consumption Rate g/A-yr	Driving Voltage, Volt**
Al-Zn-Hg	95	2.713	3084	0.2
Al-Zn-Sn	87	2.768	3356	0.2
Mg-Al-Zn***	50	1.799	7937	0.7
Zn+	95	7.141	11249	0.2
Zn++	90	7.141	11884	0.2
Mg-Mn+++	50	1.744	7937	0.9

* Percentage of anode weight available for cathodic protection; balance is consumed by self-corrosion.
** Relative to steel polarized to a potential of -0.85 volt referenced to a copper copper sulfate ($Cu\text{-}CuSO_4$) electrode.
*** Often referred to as a regular potential magnesium alloy.
+ MIL-A-18001 zinc for seawater applications.
++ High purity zinc for freshwater service.
+++ Often referred to as high potential magnesium alloy.

Impressed Current Cathodic Protection

Advantages of an impressed current cathodic protection system include:

- Applicable in high resistivity environments.
- Effective in protecting uncoated and poorly coated structures.
- Can be designed for a wide range of voltage and current outputs.
- High ampere-year outputs available from a single anode installation.
- Large areas can be protected by a single anode installation.

Limitations associated with impressed current systems include:

- Can cause cathodic interference (stray current corrosion).
- Power supplies are subject to failure.
- Anodes and their associated cables can be damaged by waterborne ice and debris.
- Periodic inspection and maintenance is required.
- Power costs.
- Overprotection can cause coating damage (disbondment), hydrogen embrittlement of high-strength steels, and "cathodic corrosion" of amphoteric metals and alloys (e.g., lead, zinc, aluminum, and their alloys).

Commonly used impressed current cathodic protection system anodes and their dissolution rates (in grams per ampere-year) are listed in Table 2. Examination of the dissolution rates reveal that systems with long life expectancy can be designed using impressed current cathodic protection, even for structures where relatively large currents might be required.

The weak link in an impressed current cathodic protection system for Civil Works structures is undoubtedly the electrical cable and connections between the anodes and the power supply. Exposed cable is especially subject to damage by waterborne ice and debris. One small "nick" in the underwater cable results in current discharge from the copper conductor and the resultant inoperation of the anodes beyond this location. Equally important, high molecular weight polyethylene (HMPE) cable insulation is subject to deterioration by the chlorine which is usually generated at the anodes in water containing high concentrations of chloride. This problem can be circumvented by using dual jacketed cable wherein the inner layer of insulation is either chlorine-resistant ethylene chlorotrifluorethylene (ECTFE) or polyvinylidene fluoride (PVF) and the outer layer is abrasion-resistant HMPE. Innovative ceramic anode assemblies are also available to prevent the premature deterioration of the anode-to-cable connections (see Chapter 4). The same concern for current discharge at locations other than the anodes also precludes the use of underwater cable splices.

Table 2

Impressed Current Anode Materials and Their Dissolution Rates

Electrode Material	Anodic Dissolution Rate (g/A-yr)
High Silicon Cast Iron	~450
Graphite	200
Cast Magnetite	40
Lead Silver Alloy (1.5% Silver)	30
Plasma Sprayed Lithium Ferrite	1.7
Sintered Nickel Ferrite	1.6
Platinum Coated Titanium	0.1
IrO_2/TiO_2	0.006 (in fresh water)
RuO_2/TiO_2	0.001 (in saltwater)

High Silicon Chromium Bearing Cast Iron (HSCBCI) anodes can be produced in many sizes and shapes. One shape which has been used for navigation lock gates is a "button anode" (Figure 1). The electrical connection in this 152-mm diameter button anode is provided through the body of the anode, and the anchoring bolt is electrically isolated from the body of the anode while electrically shorted to the gate itself to receive cathodic protection. This particular design was developed after discovering that if the anchoring bolt is electrically connected to the body of the anode, an electrical short will rapidly corrode the bolt, and the anode will fall off. A square grid of button anodes every 3 meters provides adequate protection. However, on the chamber side of a miter gate, individual button anodes are required in each compartment to prevent electrical shielding and to provide complete coverage.

The cost of a cathodic protection system can be reduced somewhat by using sausage anodes made from HSCBCI on the compartment side of a miter gate. Plastic-lined steel split pipes must be used to pro'ect these anodes from mechanical damage caused by ice and debris. These steel half-pipes act to prevent detrimental contact between the HSCBCI anodes and the waterborne ice or debris by providing a barrier between the two where contact is imminent. The opening on one side of the pipe allows the necessary current to flow for cathodic protection of the structure. However, HSCBCI anodes can still be damaged because of multiple anode to wire connections and inherent brittleness of the HSCBCI material. A satisfactory solution to this problem has been found. USACERL researchers developed a durable ceramic anode which has self-healing anode-to-anode connections and which can be mounted and protected from debris.

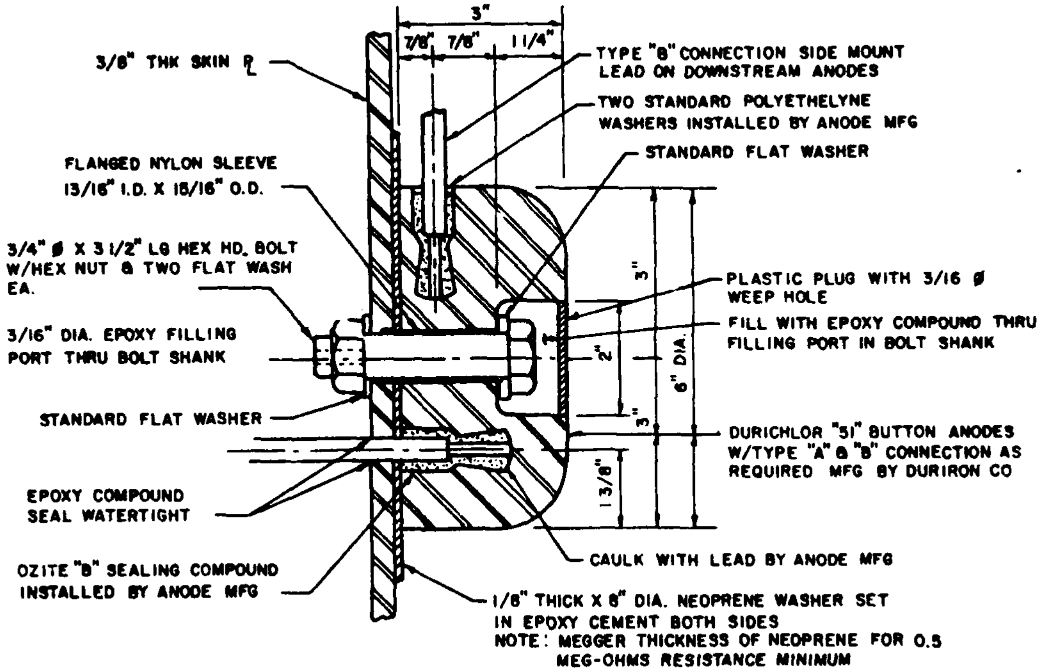

Figure 1. Bolt mount HSCBCI button anode.

3 CRITERIA FOR CATHODIC PROTECTION

National Association of Corrosion Engineers (NACE) Standard RP-01-69[7] gives the recommended practice for controlling external corrosion on underground or submerged metallic systems. The standard also details the criteria for cathodic protection. These criteria are applicable to immersed steel structures and are as follows:

1. A negative (cathodic) voltage of at least 0.85 V as measured between the structure surface and a saturated copper-copper sulfate reference electrode containing the electrode. The voltage is measured with the protective current applied. (Sacrificial anodes systems are generally judged by this criterion.)

2. A minimum negative (cathodic) voltage shift of 300 mV, produced by the application of protective current. The voltage shift is measured between the structure surface and the stable reference electrode contacting the electrolyte. This criterion of voltage shift applies to structures not in contact with dissimilar metals.

3. A minimum negative (cathodic) polarization voltage shift of 100 mV measured between the structure surface and the stable reference electrode contacting the electrolyte. This polarization voltage shift is determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage reading after the immediate shift shall be used as a base reading from which the measure of polarization decay is made.

4. A structure-to-electrolyte voltage at least as negative (cathodic) as that originally established at the beginning of the Tafel segment of the E-logI curve. This structure-to-electrolyte voltage shall be measured between the structure surface and the stable reference electrode contacting the electrolyte in the same location where voltage measurements were taken to obtain the E-logI curve. (Impressed current systems are generally judged by this criterion.)

5. A net protective current from the electrolyte into the structure surface as measured by an earth current technique applied at predetermined current discharge points on the structure.

NACE has proposed some changes to RP-01-69 which are still being evaluated. One of the changes states that the pipe-to-electrolyte potentials should be measured with the reference electrode located in the electrolyte as close as practicable to the structure. The metal contact should also be placed as close as practicable to the point of interest. Closer placement of the reference electrode to the surface of the structure under study will be more indicative of the local conditions. If the metal contact or reference electrode placement is remote from the structure surface at the point of interest, the IR drop is considered and more voltage is included in the pipe-to-electrolyte potential reading. IR drop has no direct bearing on the level of cathodic protection and should be removed from the reading before interpretation.

[7] *Recommended Practice, Control of External Corrosion on Underground or Submerged Metallic Piping Systems*, NACE Standard RP-01-69 (NACE, 1983).

The proposed change to RP-01-69 also lists the following methods for determining or minimizing the metal or electrolyte IR drops in the potential measurements:

1. Reference Electrode Placement: The electrolyte IR drop can be reduced by placing the reference electrode close to the pipe surface. This procedure does not eliminate the coating or metal IR drops.

2. Metal Contact Location: Metal IR drops can be reduced by contacting the pipe close to the point of interest. This procedure does not eliminate the coating or metal IR drops.

3. Current Interruption: Metal, electrolyte, and coating IR drops can be reduced by interrupting all currents and reading the potential before any depolarization occurs. Currents that should be interrupted include rectifiers, foreign sources of current, galvanic anodes, and spontaneous galvanic activity.

4. Step-wise Interruption of Current: The metal, electrolyte, and coating IR drops can be estimated by reducing the total current (IR) in steps and by extrapolating the cumulative IR drop measured from the steps to the total IR at zero current. The current is measured by the IR drops in the electrolyte transverse to the pipe (side-drain potentials).

The total IR drop is estimated as:

$$IR[total] = IR[partial] \frac{IR[E1]}{IR[E1] - IR[E2]}$$

where:

IR[E1] is the average side-drain potential measured on both sides of the pipe before the current-reduction step,

IR[E2] is the corresponding side-drain potentials after the current-reduction step, and

IR[partial] is the IR drop observed in the pipe-to-soil potential measured over the pipe when the current-reduction step occurs.

The estimate is accurate as long as the side-drain potentials are proportional to the IR drop measured over the pipe.

5. Distance Extrapolation: Electrolyte IR drop can be estimated by measuring the on-potential as a function of distance from the pipe and extrapolating to zero distance. This procedure does not eliminate metal or coating IR drop and assumes a homogeneous environment. Extreme care must be exercised in selecting the extrapolation formulas.

Sometimes the second criterion, the 300 mV shift, is also used for Corps structures; however, it is usually inconvenient to determine the preprotection potential. If the preprotection potential of the structure is -0.45 V with respect to a copper-copper sulfate cell, there is no need to polarize the structure to -0.85 V. A reading of -0.75 V will signify complete cathodic protection. To measure the preprotection potential of the structure, the cathodic protection will have to be shut off for approximately a week to allow depolarization to occur. Preprotection potential can also be measured before the cathodic protection system is installed and turned on.

In the third criterion, the 100 mV decay, the rectifier is shut off and the potential of the structure drops immediately (e.g., from -0.85 to -0.75 V). If the potential then decays to -0.65 V, a polarization decay of 100 mV is achieved. This criterion can also be used for Corps hydraulic structures.

Although a 100 mV shift corresponds to a complete stoppage of corrosion, this may not be necessary for adequate protection of hydraulic structures. A 50 mV shift, for example, will reduce the corrosion rate of steel in tap water by more than one-half of its unprotected value which can be demonstrated by E-logI curves as mentioned in the 4th criterion (Figure 2).

Criterion 5 proposed by NACE Standard RP-01-69 is too complex to be used under field conditions in Corps hydraulic structures.

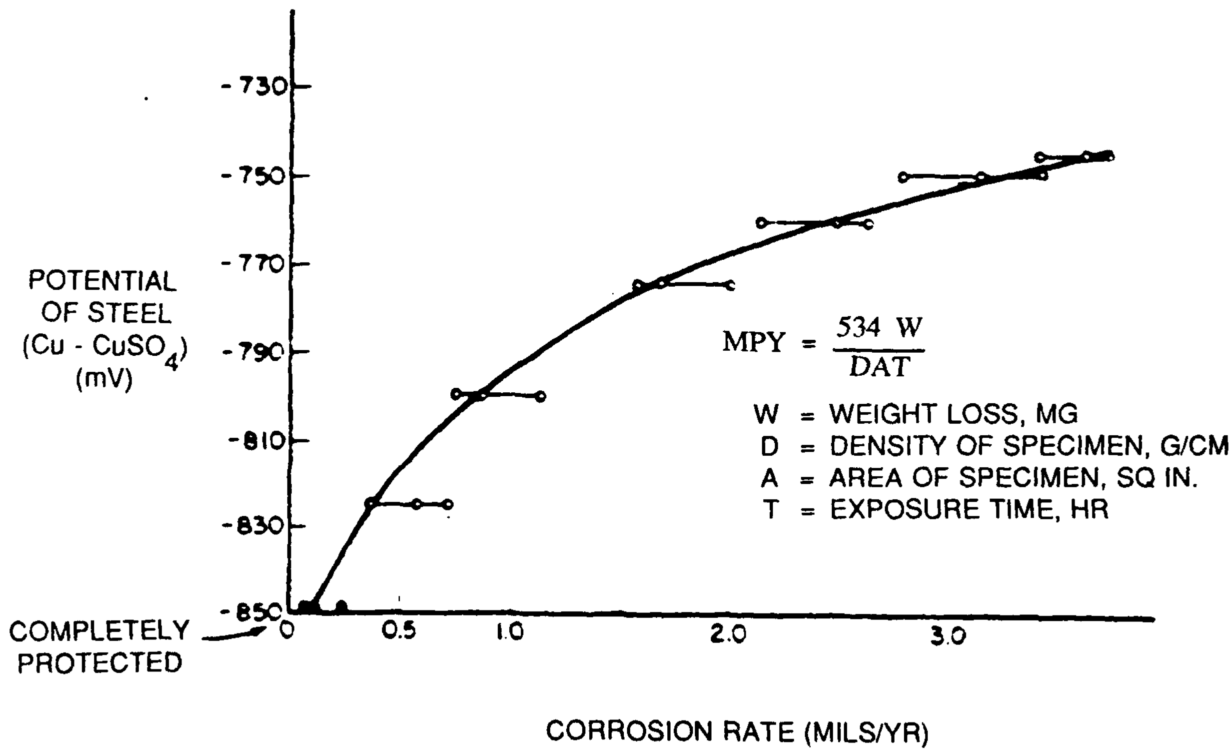

Figure 2. Corrosion rate of steel in tap water.

4 CERAMIC ANODES

Sacrificial anodes are large, brittle, not easily machined, and have dissolution rates of about 450 g/A-yr. The high dissolution rate requires the use of large anodes, which in turn are vulnerable to mechanical damage from floating debris or ice. Large anodes are also prone to installation problems. Platinized anodes consisting of a thin layer of platinum on a valve metal substrate such as titanium or niobium are available. However, they are expensive and the thin coating is susceptible to erosion or abrasion damage in high velocity water. Furthermore, platinum dissolution is accelerated by the ac ripple effect imposed by the rectifier.

A new ceramic anode (discussed in USACERL Technical Report M-87/03) consists of a mixed metal oxide film on a metal substrate. Metal oxides such as ruthenium and iridium oxides (RuO_2 and IrO_2) are known to exhibit metallic electrical conductivity over a wide range of temperatures. The main advantages of fabricating anodes from these materials are their very low resistivity (0.001 ohm-cm) and their very low dissolution rates (0.001 g/A-yr at 11A/m^2).[8]

The hardness of precious metal oxide coatings is about 6 on the Moh's hardness scale. Thus, these anodes are very resistant to abrasion. This is particularly important for cathodic protection applications where the anodes are exposed to impact or abrasion.

Damage from ice and debris and failure of the anode-to-cable connections are major causes of cathodic protection system malfunctions. The critical anode-to-wire connection on ceramic anodes is factory-fabricated and tested, eliminating related field assembly and installation difficulties. The watertight connector uses gold plated titanium pins and has a series of watertight seals.

Because the 152 mm diameter HSCBCI button anode weighs about 8.2 kg, it needs a metallic bolt for installation (Figure 1). The bolt is electrically isolated from the anode by using plastic bushings and injecting epoxy through filling ports. To circumvent installation problems, the flat ceramic disk anode uses a fiberglass reinforced plastic bolt with a titanium core for mounting (Figure 3). Since the anode is much lighter, the fiberglass bolt has sufficient strength. The cable to anode connection is made by gold-plated titanium pins with a connector plug which results in foolproof watertight seals. All connections are tested at 105,465 kg/m^2 in the factory before shipment. The ceramic disk anode can be installed under water, which eliminates the need to wait for dewatering before repairing a damaged anode.

Another new anode configuration is the rod (Figure 4). Titanium rods are coated with conductive ceramic coating. The rods are manufactured in 1.2 m lengths with threaded male and female connections on the ends. This allows flexibility in overall length. The connecting fittings are also coated with the conductive ceramic coating. A 6.1 m rod weighs only 0.5 kg, and has a current discharge life of 100 A-yr. An equivalent HCSBCI anode would weigh 45 kg, based on 450 g/A-yr. Since a threaded titanium anode rod can hang by its own weight, it reduces the possibility of a system malfunction caused by hanging by the cable. This anode can also be used in elevated water storage tanks instead of HSCBCI rods which weigh about 8.1 kg each and hang by the electrical cable. The ceramic rod anodes can support themselves because titanium is a strong metal and the rod sections are threaded together. Additional

[8] J. H Boy, A. Kumar, and M. Blyth.

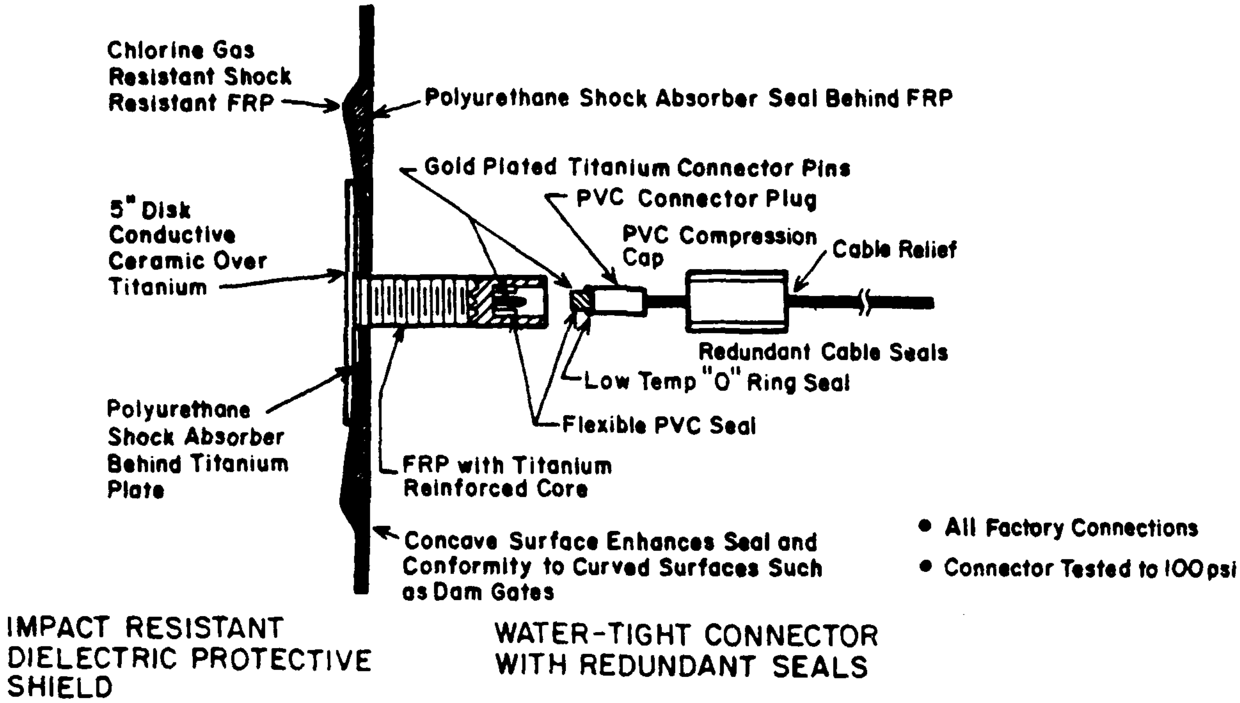

Figure 3. A flat disk ceramic anode made of conductive ceramic coating on titanium substrate.

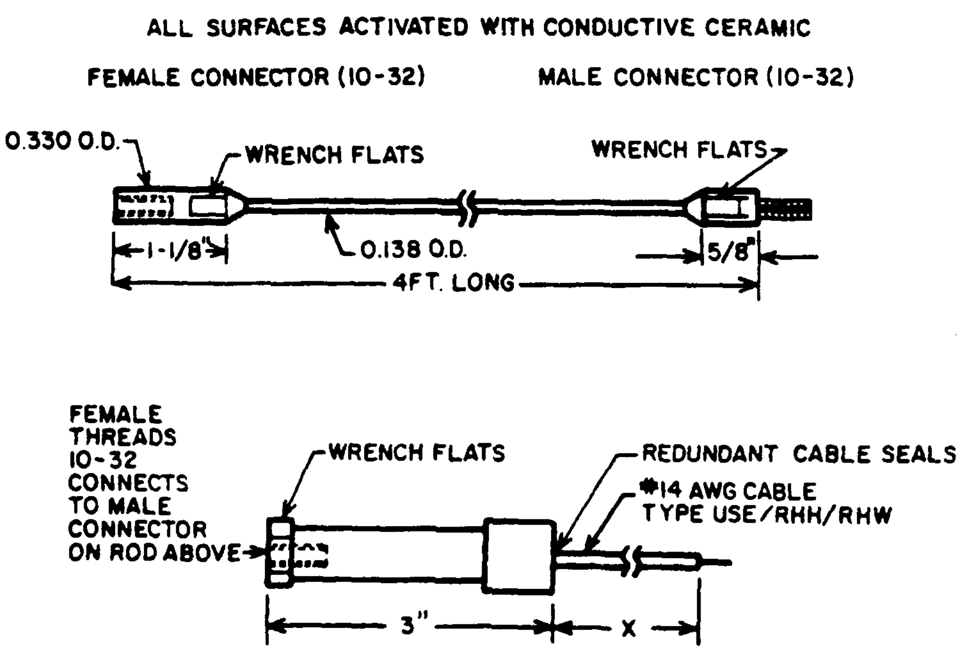

Figure 4. A rod ceramic anode.

mechanical protection to the ceramic rod anode can be provided by enclosing the anodes in perforated plastic pipes made of polyethylene or fiberglass. However, if ice and debris are present in navigation locks, split steel pipe bumpers should be used.

Because all string anodes are susceptible to physical damage, the use of perforated pipes and split steel pipe bumpers are necessary to provide a low maintenance cathodic protection system.

Impressed current cathodic protection systems using ceramic anodes have been installed at Pike Island Lock and Dam, WV and Cordell Hull Lock and Dam, TN. Based on cathodic protection potential data taken at these two locations (Appendixes A through J and Figures 5 through 9), the ceramic anode system has essentially eliminated any additional metallic corrosion. However, the previous corrosion damage remains and cannot be eliminated. Virtually every measurement point yields a potential shift far in excess of 80 mV--the level of cathodic protection necessary to satisfy the E-logI shift criterion as determined from tests performed at Pike Island Lock and Dam in 1985.

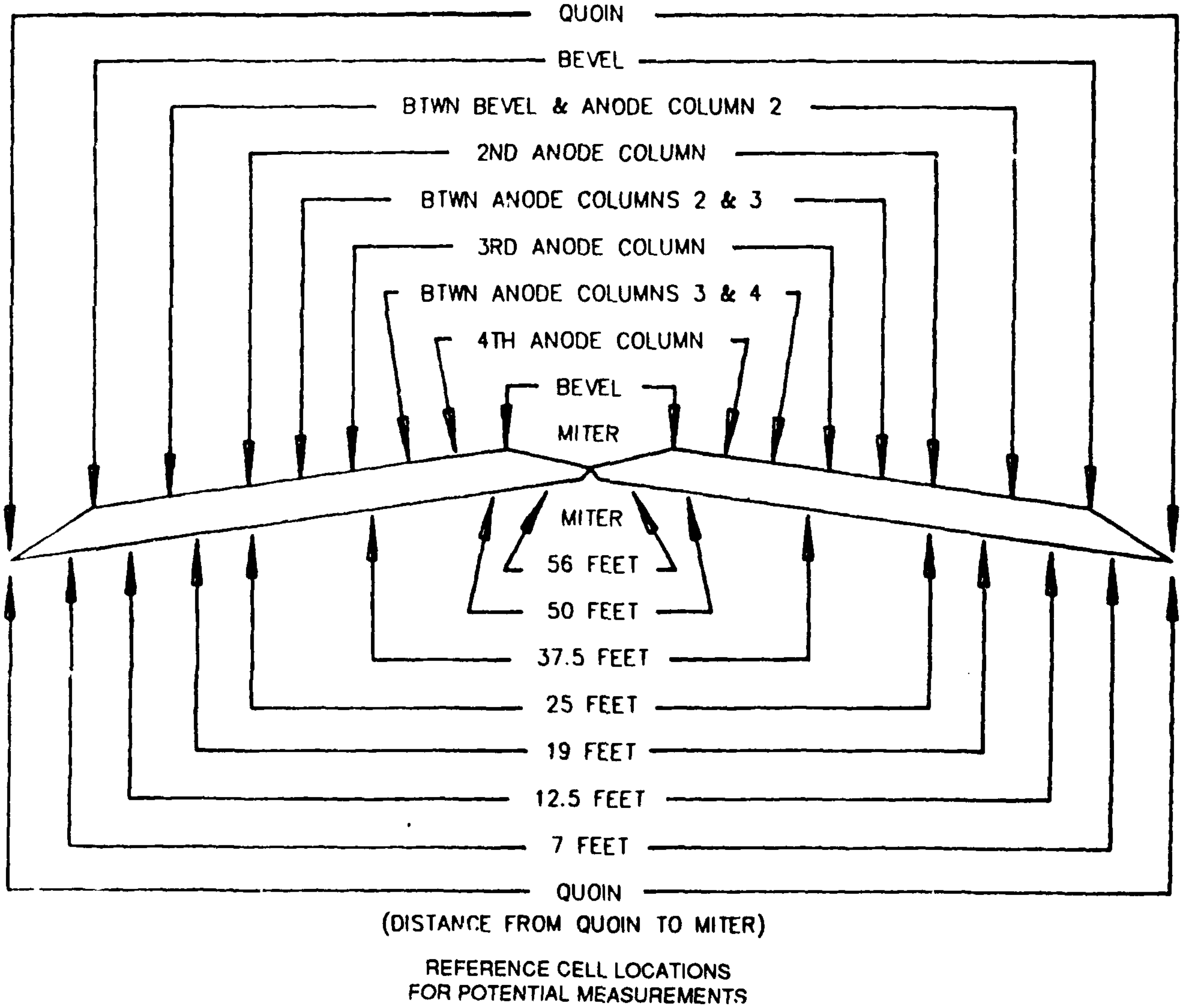

Figure 5. Top view of Pike Island Auxiliary Lock miter gate.

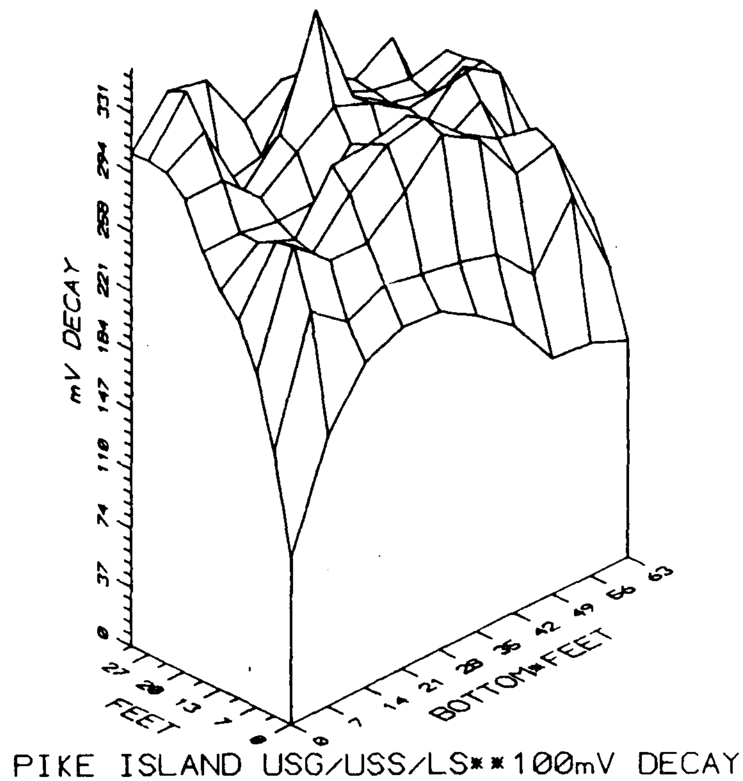

Figure 6. Pike Island Lock, upstream gate and side, land side leaf. Polarization decay/buildup is shown. "Instant Off" readings were used.

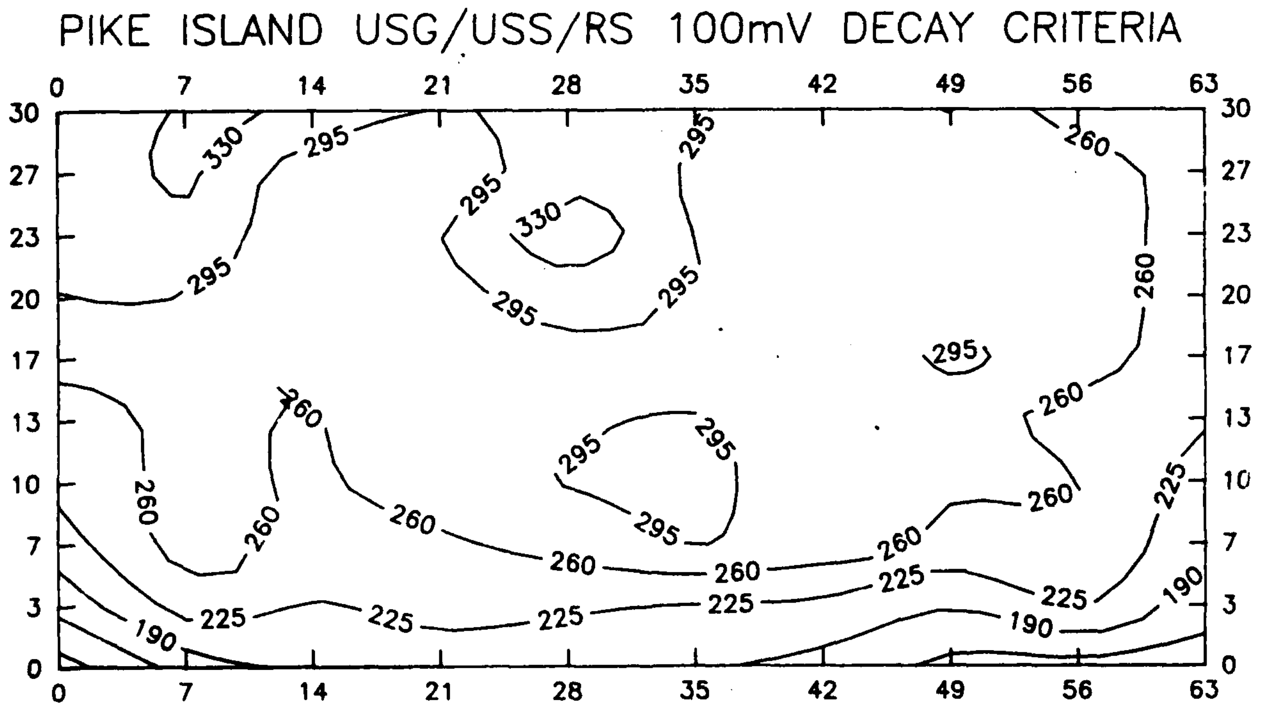

Figure 7. Pike Island usage, upstream gate and side, river side.

PIKE ISLAND USG/USS/LS 100mV DECAY CRITERIA

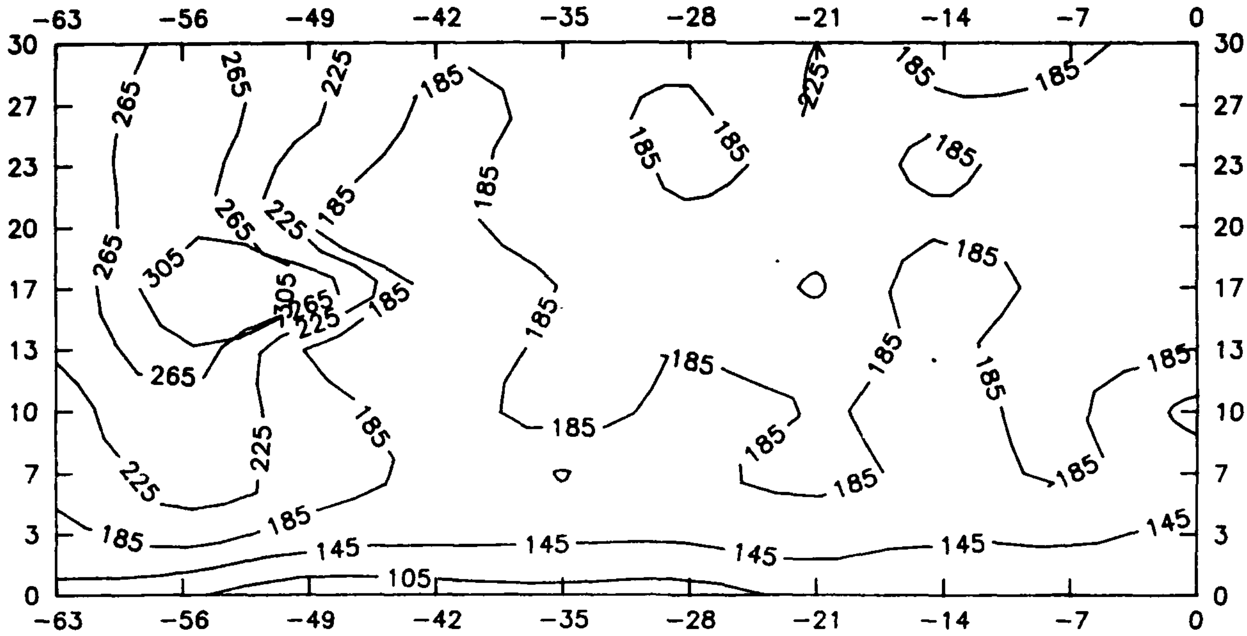

Figure 8. Pike Island usage, upstream gate and side, land side.

PIKE ISLAND USG/DSS/LS 100mV DECAY CRITERIA

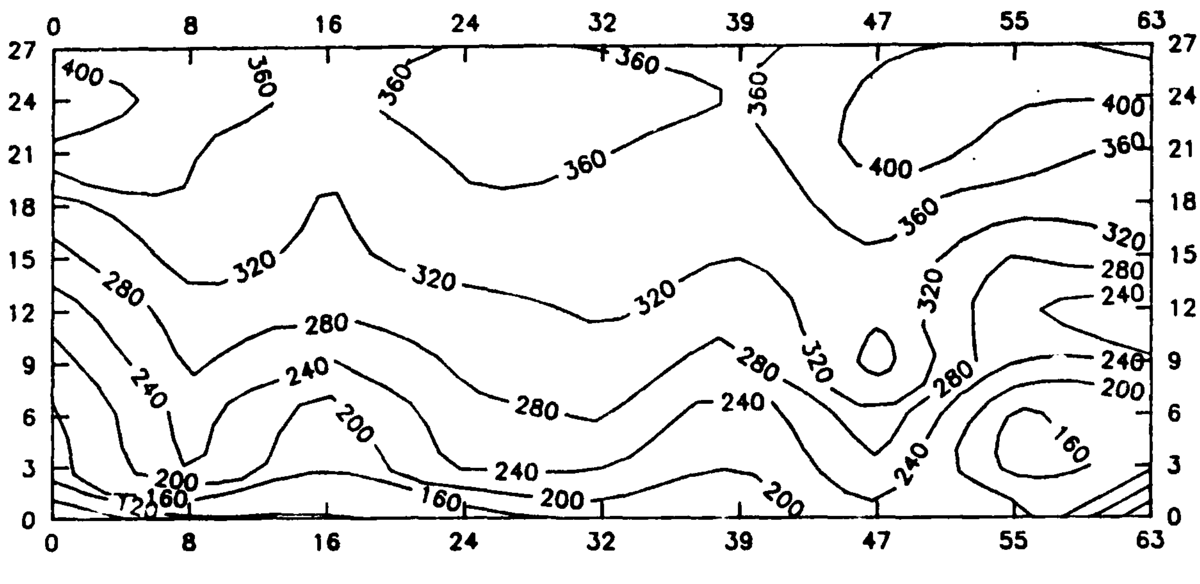

Figure 9. Pike Island usage, upstream gate, downstream side, land side.

5 ANODE DISTRIBUTION AND LOCATION

The configuration of a hydraulic structure such as a lock miter gate or a dam tainter gate determines the anode distribution and location. Lock miter gates have a skin plate on one side and compartments which are open to water on the other side. These gates are coated with a 0.015 cm thick high performance paint. The ceramic flat disk anodes are installed in a 3-m square grid on the skin side to provide adequate coverage in fresh water of resistivity 3,000 ohm-cm (Figure 10). Mounting ceramic flat disk anodes is simple. The disk anode is supported by a fiberglass reinforced plastic bolt which eliminates anode to structure "shorts." Disk anodes can also be used on the compartment side of the miter gate as well (Figure 11); individual disk anodes are installed in compartments to avoid electrical shielding problems. Disk anodes should only be used to cathodically protect compartments when the maximum protection from physical damage is necessary; otherwise, it is cheaper to use rod anodes.

To reduce the cost of installation, rod ceramic anodes can be used for the compartments (Figures 12 and 13). On an average miter gate, the number of rod anode strings on the compartment side can vary from 8 to 10. The number of anodes used should provide polarization to the miter end and the quoin end which are critical for gate alignment. Furthermore, stainless steel seals used on each end of the miter gate can cause accelerated corrosion of the areas in close proximity to the seals (within 0.5 m). The ceramic rod anodes are encased in perforated plastic pipes (Figure 13). Additional mechanical protection is provided by split steel pipe bumpers. Since the anode string (10 m long) is hung from the top of the gate, it can be easily retrieved for inspection and replacement. A detailed design for a miter gate is presented in the Appendix. Rod anodes are used to cathodically protect compartments when low resistance, high current output systems are needed.

During daily operation, locks are filled and emptied many times. When the lock is full, more anodes are in the water, thereby reducing the total resistance of the cathodic protection circuit and increasing the current. When the lock is empty, fewer anodes are in the water and the total resistance of the cathodic protection circuit is increased, which reduces the current. Because of this self-compensating effect on the resistance of the circuit, the rectifier does not need to be adjusted with each emptying and filling.

Dam tainter gates have curved surfaces and are used to regulate the flow of water. HSCBCI button anodes can be installed on such curved surfaces, but only when mounting brackets are used to support the anodes. Mounting brackets, however, have to be made of plastic or metal coated with plastic materials. However, the plastic backing on thin titanium ceramic disk anodes can bend to accommodate curved tainter gate surfaces.

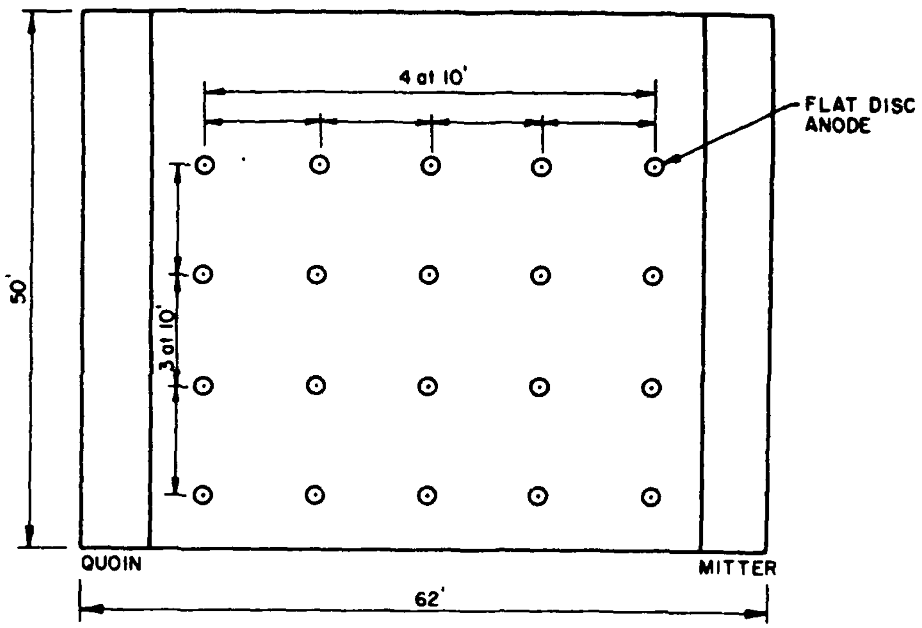

Figure 10. Diagram of flat disk ceramic anodes on the skin side of a typical navigation lock gate.

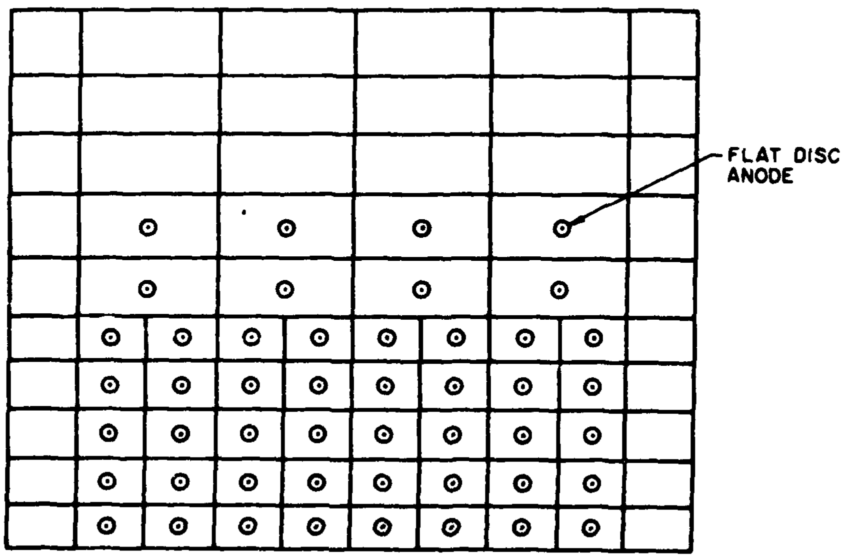

Figure 11. Diagram of flat disk ceramic anodes of the compartment side of a typical navigation lock gate.

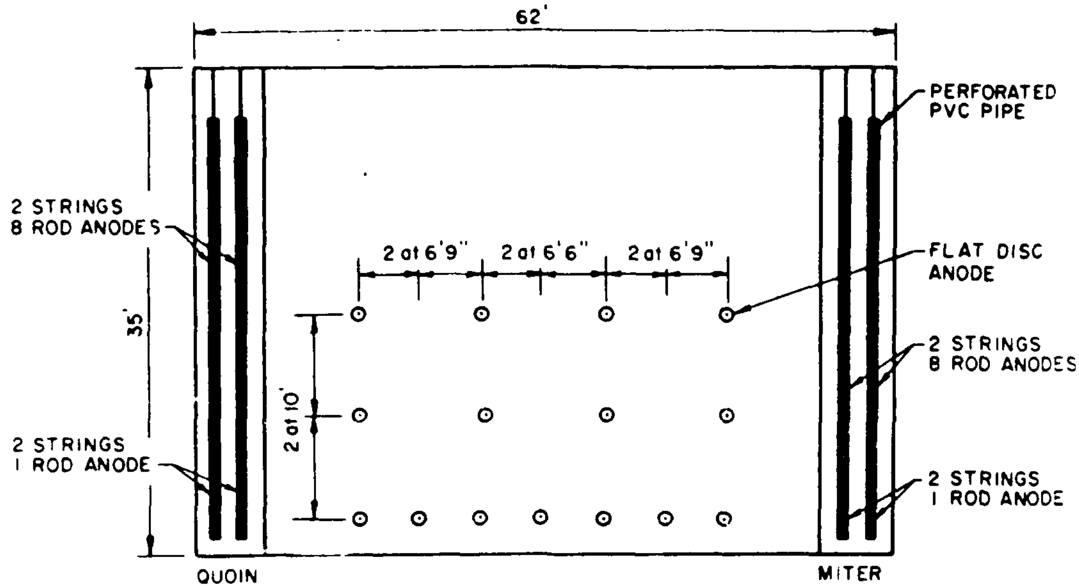

Figure 12. Diagram of flat disk and rod ceramic anodes as installed on a leaf of the upstream side of the auxiliary lock gate at Pike Island Lock and Dam, WV.

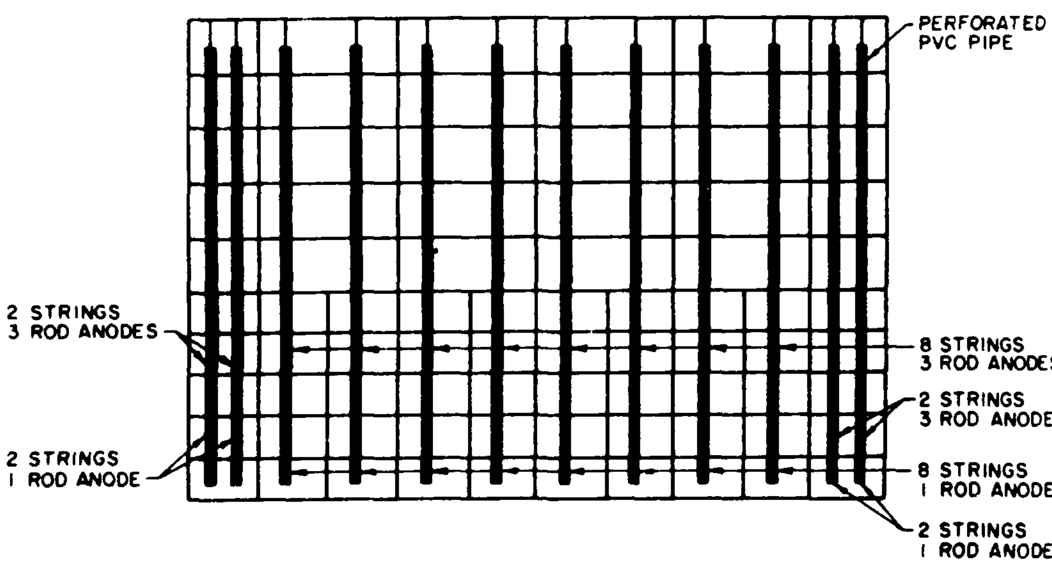

Figure 13. Diagram of rod ceramic anodes as installed on a leaf of the downstream side of the upstream auxiliary navigation lock gate at Pike Island Lock and Dam, WV.

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Ceramic anodes can be used successfully in impressed current cathodic protection systems for navigation lock and dam gates.

The low dissolution rate of the ceramic anode (0.001 g/A-yr) in fresh water enables fabrication of ceramic anodes that are much lighter than the previously used HSCBCI anodes.

The anode-to-wire connection (gold plated titanium male/female) is factory fabricated and contains a series of watertight seals that eliminate the installation problems of button type HSCBCI anodes.

Cathodic protection designs using ceramic anodes have been developed for lock and dam gates (demonstration sites are set up at Cordell Hull Dam gate in Tennessee and Pike Island miter gate in West Virginia).

Recommendations

Monitoring of the demonstration sites should continue for 2 years. This is necessary to ensure that the ceramic anode systems are resistant to ice and debris damage after a reasonable length of exposure time to such conditions. In addition, this monitoring time will allow for complete potential surveys to be taken at each site.

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APPENDIX A:

POTENTIAL SURVEY DATA OF PIKE ISLAND

PIKE ISLAND AUXILIARY LOCK
USG/USS

ISLAND WALL LEAF

Quoin (Island Wall) Bevel   Between Bevel & Anode

DEPTH ON OFF DECAY DELTA ON OFF DECAY
DELTA ON OFF DECAY DELTA

Bottom	0.818	0.796	0.697	0.099	0.873	
0.808	0.702	0.106	0.854	0.793	0.702	0.091
3	0.830	0.766	0.678	0.088	0.891	
0.808	0.703	0.105	0.896	0.797	0.632	0.165
6	1.066	0.911	0.781	0.130	1.054	
0.927	0.756	0.171	1.053	0.879	0.642	0.237
9	1.206	0.996	0.848	0.148	1.147	
0.994	0.815	0.179	1.137	0.928	0.630	0.298
12	1.293	1.026	0.686	0.340	1.149	
1.019	0.850	0.169	1.157	0.945	0.609	0.336
15	1.356	1.049	0.883	0.166	1.249	
1.023	0.845	0.178	1.209	0.963	0.614	0.349
18	1.396	1.050	0.884	0.166	1.299	
1.030	0.850	0.180	1.261	0.976	0.594	0.382
21	1.427	1.060	0.882	0.178	1.307	
1.046	0.853	0.193	1.244	0.979	0.636	0.343
24	1.450	1.053	0.878	0.175	1.350	
1.047	0.848	0.199	1.235	0.965	0.602	0.363
27	1.413	1.041	0.860	0.181	1.293	
1.048	0.818	0.230	1.213	0.951	0.573	0.378
30	1.324	1.012	0.182	0.182	1.099	
1.009	0.800	0.209	0.933	0.896	0.618	0.278

2nd Anode Column   Between Anode Columns   3rd Anode
Column

DEPTH ON OFF DECAY DELTA ON OFF DECAY
DELTA ON OFF DECAY DELTA

Bottom	0.912	0.815	0.673	0.142	0.858	
0.778	0.657	0.121	0.836	0.753	0.638	0.115
3	0.931	0.812	0.677	0.135	0.900	
0.760	0.655	0.105	0.789	0.733	0.644	0.089
6	1.209	0.888	0.704	0.184	1.300	
0.859	0.681	0.178	1.162	0.847	0.680	0.167
9	1.184	0.894	0.708	0.186	1.147	
0.901	0.679	0.222	1.149	0.885	0.688	0.197
12	1.129	0.892	0.706	0.186	1.078	
0.904	0.668	0.236	1.098	0.887	0.689	0.198
15	1.183	0.905	0.710	0.195	1.122	

0.881	0.696	0.185	1.176	0.886	0.694	0.192
18	1.583	0.966	0.721	0.245	1.147	
0.893	0.704	0.189	1.600	0.921	0.706	0.215
21	1.176	0.910	0.712	0.198	1.140	
0.905	0.703	0.202	1.178	0.897	0.698	0.199
24	1.175	0.918	0.714	0.204	1.094	
0.933	0.697	0.236	1.185	0.905	0.700	0.205
27	1.321	0.981	0.749	0.232	1.147	
0.924	0.704	0.220	1.900	0.970	0.711	0.259
30	1.189	0.929	0.722	0.207	1.156	
0.924	0.715	0.209	1.214	0.920	0.710	0.210

Between Anode Columns   4th Anode Column   Bevel

DEPTH   ON   OFF   DECAY   DELTA   ON   OFF   DECAY
DELTA   ON   OFF   DECAY   DELTA

Bottom	0.812	0.736	0.631	0.105	0.795	
0.726	0.635	0.091	0.798	0.736	0.659	0.077
3	0.805	0.733	0.628	0.105	0.771	
0.718	0.642	0.076	0.780	0.722	0.670	0.052
6	1.057	0.822	0.660	0.162	1.125	
0.844	0.675	0.169	0.993	0.865	0.711	0.154
9	1.084	0.857	0.670	0.187	1.059	
0.880	0.688	0.192	1.057	0.901	0.723	0.178
12	1.037	0.869	0.671	0.198	1.002	
0.883	0.671	0.212	1.032	0.914	0.743	0.171
15	1.052	0.874	0.676	0.198	1.031	
0.906	0.672	0.234	1.059	0.955	0.750	0.205
18	1.065	0.888	0.680	0.208	1.486	
0.960	0.689	0.271	1.205	0.992	0.788	0.204
21	1.086	0.902	0.635	0.267	1.099	
0.923	0.695	0.228	1.204	0.999	0.808	0.191
24	1.096	0.895	0.688	0.207	1.087	
0.931	0.700	0.231	1.237	0.995	0.813	0.182
27	1.102	0.908	0.696	0.212	1.413	
0.977	0.739	0.238	1.261	1.004	0.820	0.184
30	1.112	0.914	0.702	0.212	1.165	
0.956	0.734	0.222	1.199	1.017	0.820	0.197

PIKE ISLAND AUXILIARY LOCK
USG/USS

Miter

DEPTH	ON	OFF	DECAY	DELTA
Bottom	0.828	0.756	0.674	0.082
3	0.887	0.795	0.676	0.119
6	1.043	0.879	0.718	0.161
9	1.139	0.942	0.756	0.186
12	1.148	0.954	0.772	0.182
15	1.203	0.979	0.787	0.192
18	1.265	1.006	0.794	0.212
21	1.303	1.011	0.809	0.202
24	1.318	1.014	0.806	0.208
27	1.302	1.008	0.798	0.210
30	1.243	0.984	0.784	0.200

PIKE ISLAND AUXILIARY LOCK
USG/USS

LAND WALL LEAF

	Bevel				4th Anode Column				Between Anode Columns			
DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA
Bottom	0.822	0.758	0.660	0.098	0.794	0.742	0.639	0.103	0.882	0.802	0.661	0.141
3	0.835	0.797	0.673	0.124	0.797	0.743	0.641	0.102	0.873	0.781	0.663	0.118
6	1.108	0.923	0.719	0.204	0.973	0.860	0.678	0.182	0.952	0.819	0.682	0.137
9	1.273	0.968	0.739	0.229	0.950	0.873	0.692	0.181	0.986	0.855	0.696	0.159
12	1.200	0.983	0.731	0.252	0.971	0.889	0.697	0.192	0.977	0.872	0.701	0.171
15	1.170	0.980	0.746	0.234	1.062	0.916	0.713	0.203	0.990	0.884	0.709	0.175
18	1.399	1.018	0.766	0.252	1.046	0.918	0.736	0.182	1.015	0.892	0.716	0.176
21	1.502	1.042	0.787	0.255	1.068	0.915	0.730	0.185	1.022	0.900	0.718	0.182
24	1.328	1.017	0.809	0.208	1.156	0.921	0.726	0.195	1.022	0.899	0.719	0.180
27	1.399	1.027	0.804	0.223	1.056	0.935	0.741	0.194	1.036	0.903	0.724	0.179
30	1.093	0.959	0.742	0.217	1.048	0.940	0.759	0.181	1.034	0.914	0.732	0.182

	3rd Anode Columns				Between Anode Columns				2nd Anode Column			
DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA

Bottom	0.874	0.790	0.664	0.126	0.884
0.798	0.669	0.129	0.872	0.807	0.684
0.123					
3	0.838	0.788	0.668	0.120	0.851
0.780	0.668	0.112	0.908	0.812	0.692
0.120					
6	1.054	0.839	0.690	0.149	1.080
0.840	0.695	0.145	1.134	0.858	0.707
0.151					
9	1.073	0.873	0.705	0.168	1.082
0.889	0.705	0.184	1.164	0.885	0.713
0.172					
12	1.042	0.891	0.708	0.183	1.039
0.918	0.694	0.224	1.127	0.899	0.719
0.180					
15	1.074	0.893	0.711	0.182	1.109
0.901	0.714	0.187	1.159	0.908	0.723
0.185					
18	1.350	0.913	0.714	0.199	1.121
0.909	0.720	0.189	1.366	0.915	0.727
0.188					
21	1.087	0.901	0.719	0.182	1.139
0.912	0.723	0.189	1.190	0.916	0.728
0.188					
24	1.088	0.904	0.721	0.183	1.106
0.929	0.724	0.204	1.185	0.925	0.728
0.197					
27	1.219	0.914	0.727	0.187	1.102
0.929	0.729	0.200	1.269	0.926	0.730
0.196					
30	1.098	0.917	0.751	0.166	1.127
0.923	0.735	0.188	1.182	0.929	0.734
0.195					

Between Anode & Bevel Bevel Quoin (Land Wall)

DEPTH ON OFF DECAY DELTA ON OFF DECAY
DELTA ON OFF DECAY DELTA

Bottom	0.930	0.846	0.712	0.134	0.944	
0.849	0.692	0.157	0.874	0.809	0.617	0.192
3	0.962	0.860	0.719	0.141	0.970	
0.865	0.699	0.166	0.844	0.777	0.591	0.186
6	1.121	0.912	0.739	0.173	1.252	
0.990	0.745	0.245	1.108	0.924	0.728	0.196
9	1.233	0.961	0.760	0.201	1.370	
1.030	0.784	0.246	1.261	1.003	0.790	0.213
12	1.292	0.973	0.776	0.197	1.440	
1.042	0.811	0.231	1.342	1.025	0.809	0.216
15	1.380	0.997	0.784	0.213	1.61[illegible]	

PIKE ISLAND AUXILIARY LOCK
USG/DSS

ISLAND WALL LEAF

Quoin (Island Wall) 7 Feet   12.5 Feet

DEPTH   ON   OFF   DECAY   DELTA   ON   OFF   DECAY
DELTA   ON   OFF   DECAY   DELTA

Bottom	0.609	0.600	0.579	0.021	0.963	
0.879	0.733	0.146	1.070	0.911	0.803	0.108
3	0.859	0.741	0.643	0.098	0.954	
0.863	0.714	0.149	1.147	0.999	0.798	0.201
6	0.999	0.916	0.736	0.180	1.006	
0.903	0.733	0.170	1.283	1.014	0.803	0.211
9	1.063	0.903	0.765	0.138	1.074	
0.928	0.747	0.181	1.250	1.019	0.821	0.198
12	1.234	1.016	0.758	0.258	1.186	
0.943	0.752	0.191	1.336	1.024	0.816	0.208
15	1.392	1.022	0.766	0.256	1.358	
0.983	0.755	0.228	1.497	1.016	0.800	0.216
18	1.618	1.033	0.789	0.244	1.499	
0.973	0.736	0.237	1.662	1.036	0.788	0.248
21	1.799	1.046	0.749	0.297	1.638	
0.985	0.711	0.274	1.648	1.014	0.756	0.258
24	2.231	1.021	0.785	0.236	1.818	
0.984	0.692	0.292	1.917	1.030	0.738	0.292
27	2.117	1.003	0.638	0.365	1.740	
0.979	0.669	0.310	1.883	1.019	0.722	0.297

19 Feet   25 Feet   37.5 Feet

DEPTH   ON   OFF   DECAY   DELTA   ON   OFF   DECAY
DELTA   ON   OFF   DECAY   DELTA

Bottom	1.098	0.989	0.816	0.173	1.126	
0.940	0.809	0.131	1.171	1.023	0.836	0.187
3	1.202	0.996	0.817	0.179	1.210	
0.986	0.802	0.184	1.313	1.031	0.849	0.182
6	1.240	1.026	0.825	0.201	1.278	
1.016	0.817	0.199	1.398	1.070	0.861	0.209
9	1.295	1.033	0.827	0.206	1.315	
1.033	0.840	0.193	1.435	1.086	0.864	0.222
12	1.388	1.057	0.816	0.241	1.516	
1.059	0.839	0.220	1.593	1.093	0.863	0.230
15	1.492	1.050	0.819	0.231	1.699	
1.078	0.847	0.231	1.734	1.113	0.866	0.247
18	1.779	1.055	0.801	0.254	1.942	
1.092	0.828	0.264	1.965	1.102	0.850	0.252
21	1.900	1.051	0.787	0.264	2.147	

						1.087	0.816	0.271	2.367	1.116	0.834	0.282
24	2.271	1.063	0.774	0.289	2.399	1.096	0.808	0.288	2.586	1.120	0.829	0.291
27	1.780	1.064	0.760	0.304	2.056	1.089	0.795	0.294	2.667	1.127	0.823	0.304

50 Feet 56 Feet

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA
Bottom	1.188	0.986	0.830	0.156	0.960	0.856	0.737	0.119
3	1.305	1.035	0.841	0.194	1.318	1.008	0.795	0.213
6	1.405	1.065	0.860	0.205	1.399	1.059	0.841	0.218
9	1.434	1.080	0.866	0.214	1.524	1.072	0.866	0.206
12	1.583	1.100	0.862	0.238	1.683	1.083	0.863	0.220
15	1.816	1.100	0.855	0.245	1.887	1.100	0.860	0.240
18	2.057	1.103	0.848	0.255	2.385	1.123	0.830	0.293
21	2.300	1.133	0.833	0.300	2.520	1.117	0.807	0.310
24	2.617	1.142	0.812	0.330	2.645	1.113	0.787	0.326
27	2.520	1.135	0.807	0.328	2.800	1.115	0.772	0.343

PIKE ISLAND AUXILIARY LOCK
USG/DSS

Miter

DEPTH	ON	OFF	DECAY	DELTA
Bottom	0.940	0.799	0.502	0.297
3	0.910	0.808	0.701	0.107
6	1.000	0.912	0.760	0.152
9	1.167	0.959	0.759	0.200
12	1.322	1.018	0.806	0.212
15	1.473	1.057	0.811	0.246
18	1.543	1.048	0.802	0.246
21	1.892	1.118	0.779	0.339
24	2.055	1.107	0.738	0.369
27	1.905	1.059	0.660	0.399

PIKE ISLAND AUXILIARY LOCK
USG/DSS

LAND WALL LEAF

56 Feet 50 Feet 37.5 Feet

DEPTH	ON	OFF DECAY	DELTA	ON	OFF DECAY	
DELTA	ON	OFF DECAY	DELTA			
Bottom	1.107	0.894	0.730	0.164	1.011	
0.906	0.750	0.156	1.061	0.921	0.758	0.163
3	1.149	0.958	0.732	0.226	1.096	
0.933	0.730	0.203	1.188	0.991	0.742	0.249
6	1.234	1.002	0.762	0.240	1.149	
0.967	0.722	0.245	1.118	0.976	0.723	0.253
9	1.326	1.023	0.779	0.244	1.170	
0.968	0.726	0.242	1.141	0.967	0.718	0.249
12	1.495	1.072	0.802	0.270	1.355	
1.020	0.757	0.263	1.356	0.992	0.732	0.260
15	1.687	1.072	0.798	0.274	1.501	
1.047	0.764	0.283	1.491	1.026	0.734	0.292
18	1.971	1.056	0.769	0.287	1.843	
1.051	0.765	0.286	1.711	1.031	0.745	0.286
21	2.379	1.094	0.774	0.320	1.993	
1.044	0.742	0.302	1.903	1.041	0.733	0.308
24	2.699	1.095	0.759	0.336	2.110	
1.056	0.726	0.330	2.066	1.057	0.727	0.330
27	2.101	1.078	0.724	0.354	1.789	
1.036	0.708	0.328	1.722	1.032	0.707	0.325

25 Feet 19 Feet 12.5 Feet

DEPTH	ON	OFF DECAY	DELTA	ON	OFF DECAY	
DELTA	ON	OFF DECAY	DELTA			
Bottom	1.019	0.921	0.767	0.154	0.994	
0.892	0.762	0.130	0.983	0.901	0.768	0.133
3	1.148	0.961	0.716	0.245	1.005	
0.902	0.723	0.179	1.052	0.899	0.726	0.173
6	1.112	0.955	0.707	0.248	0.993	
0.884	0.695	0.189	1.086	0.928	0.715	0.213
9	1.163	0.958	0.718	0.240	1.051	
0.917	0.695	0.222	1.114	0.928	0.717	0.211
12	1.486	1.006	0.723	0.283	1.184	
0.945	0.699	0.246	1.290	0.964	0.703	0.261
15	1.566	1.002	0.714	0.288	1.242	

						0.939	0.685	0.254	1.428	0.984	0.694	0.290
18	1.699	1.006	0.708	0.298	1.327	0.955	0.680	0.275	1.621	0.970	0.676	0.294
21	1.734	1.008	0.695	0.313	1.394	0.954	0.663	0.291	1.672	0.981	0.663	0.318
24	1.775	0.996	0.692	0.304	1.521	0.966	0.660	0.306	1.726	0.984	0.635	0.349
27	1.600	1.003	0.676	0.327	1.348	0.934	0.646	0.288	1.376	0.918	0.611	0.307

7 Feet Quoin (Land Wall)

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA
Bottom	0.821	0.702	0.735		0.654	0.638	0.534	0.104
3	0.818	0.762	0.676	0.086	1.079	0.805	0.622	0.183
6	0.818	0.746	0.652	0.094	0.935	0.760	0.662	0.098
9	0.905	0.796	0.654	0.142	0.840	0.716	0.611	0.105
12	1.027	0.829	0.672	0.157	0.963	0.796	0.618	0.178
15	1.130	0.867	0.652	0.215	0.987	0.865	0.624	0.241
18	1.307	0.893	0.648	0.245	1.143	0.831	0.573	0.258
21	1.448	0.873	0.620	0.253	1.499	0.850	0.565	0.285
24	1.574	0.892	0.589	0.303	2.158	0.888	0.528	0.360
27	1.409	0.856	0.570	0.286	1.787	0.887	0.419	0.468

PIKE ISLAND AUXILIARY LOCK
DSG/USS

ISLAND WALL LEAF

Quoin (Island Wall) Bevel   Between Bevel & Anode

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY
DELTA	ON	OFF	DECAY	DELTA			
Bottom	1.040	0.945	0.804	0.141	1.119		
0.962	0.820	0.142	1.072	0.957	0.824	0.133	
3	0.927	0.818	0.660	0.158	1.149		
0.965	0.815	0.150	1.097	0.969	0.827	0.142	
6	1.088	0.941	0.800	0.141	1.290		
1.015	0.835	0.180	1.240	0.981	0.819	0.162	
9	1.326	1.041	0.854	0.187	1.436		
1.057	0.857	0.200	1.342	0.999	0.815	0.184	
12	1.540	1.083	0.864	0.219	1.633		
1.097	0.853	0.244	1.399	1.013	0.819	0.194	
15	1.524	1.086	0.856	0.230	1.724		
1.104	0.843	0.261	1.440	1.029	0.812	0.217	
18	1.431	1.030	0.829	0.201	1.690		
1.137	0.842	0.295	1.457	1.039	0.810	0.221	
21	1.560	1.068	0.809	0.259	1.735		
1.102	0.883	0.219	1.581	1.035	0.805	0.230	
24	1.735	1.082	0.812	0.270	1.999		
1.104	0.836	0.268	1.647	1.011	0.790	0.229	
27	1.899	1.100	0.807	0.293	2.276		
1.076	0.811	0.265	1.830	1.020	0.784	0.236	
30	2.299	1.108	0.797	0.311	2.489		
1.068	0.805	0.263	1.947	1.021	0.775	0.246	
33	2.530	1.103	0.772	0.331	2.704		
1.064	0.785	0.279	1.961	1.017	0.768	0.249	
36	2.470	1.094	0.750	0.344	3.280		
1.105	0.765	0.340	1.999	1.021	0.756	0.265	
39	2.434	1.099	0.728	0.371	2.566		
1.086	0.755	0.331	1.899	1.012	0.753	0.259	

2nd Anode Column   Between Anode Columns   3rd Anode Column

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF*	DECAY
DELTA	ON	OFF	DECAY	DELTA			
Bottom	1.073	0.947	0.776	0.171	1.052		
0.780	0.759	0.021	1.038	0.915	0.744	0.171	
3	1.066	0.941	0.777	0.164	1.051		

0.787	0.756	0.031	1.023	0.920	0.743	0.177
6	1.252	0.933	0.771	0.162	1.201	
0.776	0.753	0.023	1.175	0.908	0.748	0.160
9	1.229	0.935	0.760	0.175	1.189	
0.762	0.742	0.020	1.178	0.911	0.729	0.182
12	1.238	0.945	0.758	0.187	1.133	
0.748	0.732	0.016	1.165	0.923	0.722	0.201
15	1.252	0.958	0.760	0.198	1.022	
0.720	0.724		1.184	0.925	0.715	0.210
18	1.172	0.963	0.768	0.195	1.128	
0.754	0.731	0.023	1.112	0.911	0.707	0.204
21	1.690	0.932	0.751	0.181	1.161	
0.756	0.731	0.025	1.543	0.905	0.716	0.189
24	1.278	0.931	0.737	0.194	1.178	
0.737	0.714	0.023	1.195	0.884	0.705	0.179
27	1.299	0.918	0.729	0.189	1.100	
0.699	0.681	0.018	1.207	0.877	0.701	0.176
30	1.500	0.919	0.724	0.195	1.100	
0.703	0.696	0.007	1.396	0.882	0.702	0.180
33	1.374	0.906	0.722	0.184	1.275	
0.723	0.709	0.014	1.313	0.883	0.704	0.179
36	1.506	0.913	0.719	0.194	1.314	
0.725	0.711	0.014	1.690	0.897	0.706	0.191
39	1.397	0.914	0.721	0.193	1.190	
0.726	0.711	0.015	1.336	0.879	0.705	0.174

* The current interrupter was not functioning during this "OFF" column of data invalidating the "OFF" and "DELTA" data at this point on the gate.

PIKE ISLAND AUXILIARY LOCK
DSG/USS

ISLAND WALL LEAF

Between Anode Columns   4th Anode Column   Bevel

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY
DELTA	ON	OFF	DECAY	DELTA			
Bottom	1.023	0.911	0.741	0.170	0.982		
0.882	0.742	0.140	1.037	0.887	0.750		
0.137		3	1.007	0.903	0.733	0.170	
0.969	0.876	0.726	0.150	1.060	0.990		
0.746	0.244				6	1.158	
0.893	0.728	0.165	1.158	0.908	0.723		
0.185	1.164	0.945	0.745	0.200			
9	1.144	0.893	0.715	0.178	1.113		
0.912	0.702	0.210	1.199	1.000	0.822	0.178	
12	1.072	0.875	0.704	0.171	1.105		
0.882	0.690	0.192	1.199	0.990	0.809	0.181	
15	1.012	0.861	0.684	0.177	1.063		
0.849	0.692	0.157	1.529	1.007	0.775	0.232	
18	0.839	0.770	0.637	0.133	0.824		
0.747	0.668	0.079	1.400	1.018	0.782	0.236	
21	1.028	0.844	0.658	0.186	1.297		
0.889	0.701	0.188	1.600	1.011	0.747	0.264	
24	1.108	0.864	0.685	0.179	1.229		
0.873	0.699	0.174	2.299	1.007	0.755	0.252	
27	1.146	0.866	0.694	0.172	1.300		
0.885	0.691	0.194	2.160	0.977	0.741	0.236	
30	1.080	0.860	0.696	0.164	1.522		
0.896	0.697	0.199	2.315	0.971	0.729	0.242	
33	1.238	0.875	0.698	0.177	1.500		
0.889	0.698	0.191	2.565	0.978	0.720	0.258	
36	1.287	0.871	0.698	0.173	2.421		
0.942	0.694	0.248	2.431	0.964	0.699	0.265	
39	1.294	0.873	0.697	0.176	1.440		
0.904	0.686	0.218	1.851	0.936	0.652		
0.284							

Miter

DEPTH	ON	OFF	DECAY	DELTA
Bottom	1.041	0.885	0.750	0.135
3	1.033	0.898	0.753	0.145
6	1.189	0.947	0.767	0.180

9	1.271	0.993	0.780	0.213
12	1.343	1.002	0.779	0.223
15	1.318	0.963	0.763	0.200
18	1.113	0.834	0.730	0.104
21	1.069	0.836	0.687	0.149
24	1.466	0.927	0.706	0.221
27	1.655	0.965	0.711	0.254
30	1.894	0.951	0.703	0.248
33	1.727	0.930	0.704	0.226
36	1.600	0.903	0.691	0.212

PIKE ISLAND AUXILIARY LOCK
DSG/USS

LAND WALL LEAF

Bevel 4th Anode Column Between Anode Columns

DEPTH ON OFF DECAY DELTA ON OFF DECAY
DELTA ON OFF DECAY DELTA

Bottom	1.043	0.865	0.753	0.112	1.007
0.877	0.754	0.123	0.965	0.865	0.764
0.101					
3	1.072	0.897	0.756	0.141	0.966
0.864	0.749	0.115	0.950	0.866	0.768
0.098					
6	1.299	0.963	0.790	0.173	0.999
0.887	0.745	0.142	1.109	0.883	0.749
0.134					
9	1.239	1.000	0.771	0.229	1.068
0.870	0.729	0.141	1.135	0.877	0.734
0.143					
12	1.503	0.999	0.787	0.212	1.039
0.866	0.705	0.161	1.054	0.867	0.719
0.148					
15	1.489	1.005	0.760	0.245	1.138
0.888	0.688	0.200	1.006	0.861	0.698
0.163					
18	1.399	1.047	0.733	0.314	0.896
0.820	0.613	0.207	0.836	0.777	0.653
0.124					
21	1.348	1.034	0.733	0.301	1.200
0.896	0.701	0.195	0.950	0.814	0.682
0.132					
24	1.799	0.996	0.746	0.250	1.257
0.892	0.699	0.193	1.109	0.860	0.700
0.160					
27	2.020	0.989	0.734	0.255	1.317
0.909	0.705	0.204	1.184	0.881	0.708
0.173					
30	2.600	1.011	0.733	0.278	1.463
0.915	0.708	0.207	1.240	0.885	0.685
0.200					
33	2.215	0.992	0.731	0.261	1.478
0.909	0.707	0.202	1.283	0.892	0.704
0.188					
36	1.684	0.937	0.720	0.217	2.004
0.906	0.700	0.206	1.315	0.899	0.705
0.194					
39	1.399	0.890	0.709	0.181	1.419
0.909	0.684	0.225	1.322	0.894	0.705
0.189					

3rd Anode Columns Between Anode Columns 2nd Anode Column

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY
DELTA	ON	OFF	DECAY	DELTA			

Bottom	0.964	0.870	0.768	0.102	0.980	
0.882	0.780	0.102	1.053	0.935	0.796	0.139
3	0.990	0.888	0.777	0.111	0.999	
0.904	0.787	0.117	1.049	0.938	0.798	0.140
6	1.162	0.903	0.764	0.139	1.172	
0.919	0.776	0.143	1.199	0.951	0.790	0.161
9	1.165	0.907	0.753	0.154	1.177	
0.915	0.762	0.153	1.225	0.941	0.781	0.160
12	1.147	0.899	0.746	0.153	1.137	
0.913	0.748	0.165	1.200	0.945	0.774	0.171
15	1.163	0.901	0.744	0.157	1.078	
0.901	0.720	0.181	1.216	0.969	0.777	0.192
18	0.954	0.848	0.743	0.105	0.999	
0.887	0.754	0.133	1.163	0.957	0.787	0.170
21	1.194	0.880	0.732	0.148	1.086	
0.902	0.756	0.146	1.367	0.944	0.780	0.164
24	1.157	0.876	0.723	0.153	1.147	
0.907	0.737	0.170	1.263	0.925	0.760	0.165
27	1.192	0.884	0.718	0.166	1.112	
0.914	0.699	0.215	1.290	0.924	0.749	0.175
30	1.399	0.897	0.714	0.183	1.173	
0.917	0.703	0.214	1.460	0.926	0.743	0.183
33	1.313	0.894	0.716	0.178	1.272	
0.912	0.723	0.189	1.373	0.921	0.743	0.178
36	1.483	0.902	0.716	0.186	1.301	
0.920	0.725	0.195	1.565	0.926	0.740	0.186
39	1.337	0.892	0.718	0.174	1.307	
0.901	0.726	0.175	1.368	0.923	0.738	0.185

PIKE ISLAND AUXILIARY LOCK
DSG/USS

LAND WALL LEAF

Between Anode & Bevel   Quoin (Land Wall)   Bevel

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY
DELTA	ON	OFF	DECAY	DELTA			
Bottom	1.211	0.991	0.836	0.155	1.173		
0.996	0.829	0.167	1.160	1.005	0.838	0.167	
3	1.224	0.999	0.835	0.164	1.016		
0.871	0.818	0.053	1.190	1.030	0.829	0.201	
6	1.322	1.013	0.853	0.160	1.426		
1.022	0.823	0.199	1.433	1.038	0.860	0.178	
9	1.445	1.031	0.852	0.179	1.566		
1.074	0.875	0.199	1.701	1.058	0.886	0.172	
12	1.499	1.038	0.850	0.188	1.595		
1.089	0.897	0.192	1.693	1.068	0.884	0.184	
15	1.532	1.045	0.846	0.199	1.700		
1.071	0.891	0.180	1.726	1.066	0.873	0.193	
18	1.594	1.040	0.840	0.200	1.690		
1.047	0.866	0.181	1.800	1.061	0.867	0.194	
21	1.671	1.033	0.835	0.198	1.766		
1.064	0.858	0.206	1.836	1.065	0.869	0.196	
24	1.689	1.018	0.820	0.198	1.809		
1.071	0.862	0.209	1.935	1.064	0.865	0.199	
27	1.723	1.009	0.813	0.196	1.914		
1.065	0.857	0.208	1.989	1.054	0.839	0.215	
30	1.807	1.011	0.802	0.209	2.021		
1.065	0.847	0.218	2.148	1.037	0.830	0.207	
33	1.790	0.998	0.795	0.203	1.924		
1.038	0.832	0.206	2.200	1.025	0.827	0.198	
36	1.739	1.002	0.789	0.213	1.672		
1.002	0.816	0.187	1.899	1.025	0.808	0.217	
39	1.698	0.990	0.786	0.204	1.580		
0.997	0.805	0.192	1.738	1.013	0.801	0.212	

PIKE ISLAND AUXILIARY LOCK
DSG/DSS

ISLAND WALL LEAF

Quoin (Island Wall) 7 Feet 12.5 Feet

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY
DELTA	ON	OFF	DECAY	DELTA			
Bottom	0.842	0.789	0.769	0.020	1.285		
1.019	0.787	0.232	1.311	1.085	0.898	0.187	
3	1.799	1.027	0.738	0.289	1.180		
1.002	0.790	0.212	1.600	1.075	0.868	0.207	
6	1.650	0.995	0.757	0.238	1.198		
1.003	0.785	0.218	1.538	1.085	0.859	0.226	
9	1.351	1.011	0.730	0.281	1.265		
1.003	0.762	0.241	1.572	1.077	0.843	0.234	
12	1.245	0.976	0.694	0.282	1.278		
1.001	0.746	0.255	1.578	1.078	0.801	0.277	
15	1.263	0.914	0.602	0.312	1.328		
0.997	0.685	0.312	1.541	1.065	0.751	0.314	

19 Feet 25 Feet 37.5 Feet

DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY
DELTA	ON	OFF	DECAY	DELTA			
Bottom	1.352	1.036	0.866	0.170	1.320		
1.066	0.859	0.207	1.387	1.095	0.869	0.226	
3	1.383	1.076	0.849	0.227	1.507		
1.092	0.861	0.231	1.650	1.110	0.854	0.256	
6	1.465	1.092	0.846	0.246	1.599		
1.093	0.855	0.238	1.699	1.118	0.840	0.278	
9	1.521	1.091	0.829	0.262	1.613		
1.097	0.850	0.247	1.770	1.112	0.833	0.279	
12	1.554	1.095	0.802	0.293	1.721		
1.104	0.825	0.279	1.690	1.106	0.813	0.293	
15	1.541	1.084	0.755	0.329	1.780		
1.102	0.738	0.364	1.599	1.110	0.751	0.359	

50 Feet 56 Feet

DEPTH ON OFF DECAY DELTA ON OFF DECAY
DELTA

Bottom	1.296	1.036	0.885	0.151	1.414	1.058	0.788	0.270
3	1.641	1.093	0.881	0.212	1.512	1.060	0.871	0.189
6	1.689	1.115	0.863	0.252	1.799	1.097	0.876	0.221
9	1.619	1.123	0.847	0.276	1.846	1.109	0.864	0.268
12	1.629	1.111	0.834	0.277	1.754	1.109	0.841	0.268
15	1.599	1.100	0.767	0.333	1.726	1.114	0.770	0.344

Miter

DEPTH	ON	OFF	DECAY	DELTA
Bottom	1.275	0.976	0.697	0.279
3	1.234	1.016	0.791	0.225
6	1.536	1.074	0.847	0.227
9	1.444	1.099	0.848	0.251
12	1.440	1.088	0.825	0.263
15	1.531	1.070	0.754	0.316

PIKE ISLAND AUXILIARY LOCK
DSG/DSS

LAND WALL SIDE

	56 Feet				50 Feet				37.5 Feet			
DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA
Bottom	1.092	0.887	0.747	0.140	1.368	1.054	0.875	0.179	1.304	1.068	0.942	0.126
3	1.850	1.052	0.863	0.189	1.491	1.096	0.874	0.222	1.491	1.087	0.902	0.185
6	1.759	1.107	0.884	0.223	1.452	1.098	0.882	0.216	1.563	1.098	0.883	0.215
9	1.858	1.117	0.869	0.248	1.493	1.115	0.881	0.234	1.563	1.102	0.887	0.215
12	1.709	1.101	0.856	0.245	1.563	1.108	0.852	0.256	1.550	1.105	0.867	0.238
15	1.549	1.080	0.767	0.313	1.538	1.087	0.782	0.305	1.399	1.064	0.811	0.253

	25 Feet				19 Feet				12.5 Feet			
DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA
Bottom	1.270	1.041	0.884	0.157	1.304	1.049	0.887	0.162	1.308	1.065	0.898	0.167
3	1.380	1.071	0.890	0.181	1.361	1.065	0.881	0.184	1.500	1.090	0.905	0.185
6	1.540	1.109	0.877	0.232	1.464	1.082	0.871	0.211	1.600	1.088	0.868	0.220
9	1.360	1.102	0.876	0.226	1.491	1.090	0.856	0.234	1.584	1.089	0.851	0.238
12	1.638	1.104	0.852	0.252	1.508	1.086	0.827	0.259	1.561	1.065	0.822	0.243
15	1.429	1.066	0.807	0.259	1.499	1.071	0.778	0.293	1.415	1.037	0.749	0.288

	7 Feet				Quoin (Land Wall)			
DEPTH	ON	OFF	DECAY	DELTA	ON	OFF	DECAY	DELTA
Bottom	1.278	1.027	0.875	0.152	0.906	0.810	0.778	0.032

3	1.283	1.016	0.839	0.177	1.297
0.955	0.812	0.143			
6	1.277	1.000	0.802	0.198	1.241
0.957	0.773	0.184			
9	1.267	1.006	0.771	0.235	1.238
1.008	0.759	0.249			
12	1.264	1.007	0.746	0.261	1.300
0.994	0.717	0.277			
15	1.384	1.025	0.713	0.312	1.000
0.954	0.616	0.338			

APPENDIX B:

CERANODE DATA—PIKE ISLAND RECTIFIERS AND TERMINAL BOXES

PIKE ISLAND RECTIFIER
(RIVER WALL - UPG)
8/21/89

Manufacturer: Goodall

Model: TIAYCD 24-40/30/16/GGNPSZ

Type: 0031451 - 4 Circuits

Serial Number: 86A1084

Primary: 480 VAC, 2.39/1.27 Amperes, Single Phase, 60 Hz, 45oC

Output: 24/24 Volts, 3/16 Amperes

OPERATING DATA

CIRCUIT #1	CIRCUIT #2	CIRCUIT #3	CIRCUIT #4
25.87 Volts	17.80 Volts	17.73 Volts	9.78 Volts
12.78 Amperes	6.00 Amperes	2.71 Amperes	0.68 Amperes

TERMINAL BOX DATA

Anode String		Anode String		Anode String		Anode Disk	
EAR No.	Amperes	EAR No.	Amperes	EAR No.	Amperes	LSA No.	Amperes
E2	1.60	A2	0.80	A1	0.15	1	0.045
F2	1.60	B2	0.70	B1	0.19	2	0.045
G2	1.50	C2	0.70	C1	0.17	3	0.045
H2	1.70	D2	0.70	D1	0.14	4	0.045
I2	1.60	M2	0.80	E1	0.16	5	0.045
J2	1.50	N2	0.80	F1	0.18	6	0.045
K2	1.70	O2	0.70	G1	0.14	7	0.045
L2	1.50	P2	0.70	H1	0.18	8	0.045
				I1	0.16	9	0.045
				J1	0.19	10	0.045
				K1	0.17	11	0.045
				L1	0.20	12	0.045
				M1	0.18	13	0.045
				N1	0.17	14	0.045
				O1	0.12	15	0.045
				P1	0.21		

PIKE ISLAND RECTIFIER
(LAND WALL - USG)
8/21/89

Manufacturer: Goodall

Model: CSAWSD - 24/30
HNPSE - 24/16

Type: 0031449

Serial Number: 86C1951 - 2 Circuits

Primary: 480 VAC, 2.39/1.27 Amperes, Single Phase, 60 Hz, 45oC

Output: 24/24 Volts, 3/16 Amperes

OPERATING DATA

CIRCUIT #1	CIRCUIT #2
28.55 Volts	5.12 Volts
23.52 Amperes	0.56 Amperes

TERMINAL BOX DATA

Anode String		Anode Disk	
EAR No.	Amperes	LSA No.	Amperes
A	43.4	1	0.037
B	37.0	2	0.037
C	40.2	3	0.037
D	41.4	4	0.037
E	37.9	5	0.037
F	40.8	6	0.037
G	41.4	7	0.037
H	38.2	8	0.037
		9	0.037
		10	0.037
		11	0.037
		12	0.037
		13	0.037
		14	0.037
		15	0.037

PIKE ISLAND RECTIFIER
(RIVER WALL- DSG)
8/21/89

Manufacturer: Goodall

Model: CSAWSD - 24/30
HNPSE - 24/16

Type: 0031449 - 2 Circuits

Serial Number: 86C1950

Primary: 480 VAC, 2.39/1.27 Amperes, Single Phase, 60 Hz, 45oC

Output: 24/24 Volts, 3/16 Amperes

OPERATING DATA

CIRCUIT #1	CIRCUIT #2
28.61 Volts	5.22 Volts
24.84 Amperes	0.48 Amperes

TERMINAL BOX DATA

Anode String		Anode Disk	
EAR No.	Amperes	LSA No.	Amperes
A	2.40	1	0.021
B	2.50	2	0.021
C	2.40	3	0.021
D	2.30	4	0.021
E	2.20	5	0.021
F	3.30	6	0.021
G	3.20	7	0.021
H	2.70	8	0.021
		9	0.021
		10	0.021
		11	0.021
		12	0.021
		13	0.021
		14	0.021
		15	0.021
		16	0.021
		17	0.021
		18	0.021
		19	0.021
		20	0.021
		21	0.021
		22	0.021
		23	0.021

PIKE ISLAND RECTIFIER
(LAND WALL- DSG)
8/21/89

Manufacturer: Goodall

Model: CSAWSD - 24/30
HNPSE - 24/16

Type: 0031449 - 2 Circuits

Serial Number: 86C1949

Primary: 480 VAC, 2.39/1.27 Amperes, Single Phase, 60 Hz, 45oC

Output: 24/24 Volts, 3/16 Amperes

OPERATING DATA

CIRCUIT #1	CIRCUIT #2
28.18 Volts	5.14 Volts
24.72 Amperes	0.48 Amperes

TERMINAL BOX DATA

Anode String		Anode Disk	
EAR No.	Amperes	LSA No.	Amperes
A	2.20	1	0.021
B	2.40	2	0.021
C	2.70	3	0.021
D	2.20	4	0.021
E	2.30	5	0.021
F	2.80	6	0.021
G	3.10	7	0.021
H	2.70	8	0.021
		9	0.021
		10	0.021
		11	0.021
		12	0.021
		13	0.021
		14	0.021
		15	0.021
		16	0.021
		17	0.021
		18	0.021
		19	0.021
		20	0.021
		21	0.021
		22	0.021
		23	0.021

APPENDIX C:

CERANODE SURVEY DATA FOR CORDELL HULL DAM, SOUTH TAINTER GATE

CORDELL HULL READINGS
(8/25/89)

A B

ON OFF IOP DECAY DELTA ON OFF IOP
DECAY DELTA

Bottom	1.313	0.853	0.917	0.681	0.236
1.457	0.798	0.879	0.666	0.213	
3	1.310	0.814	0.884	0.705	0.179
1.502	0.759	0.845	0.624	0.221	
6	1.302	0.801	0.883	0.662	0.221
1.519	0.735	0.823	0.602	0.221	
9	1.277	0.839	0.916	0.684	0.232
1.694	0.715	0.806	0.599	0.207	
12	1.076	0.809	0.867	0.684	0.183
1.623	0.675	0.715	0.587	0.128	
15	0.966	0.817	0.872	0.688	0.184
1.520	0.633	0.702	0.580	0.122	
18	0.944	0.798	0.857	0.746	0.111
1.737	0.610	0.691	0.580	0.111	
21	0.979	0.858	0.907	0.785	0.122
1.505	0.643	0.751	0.589	0.162	
24	0.986	0.848	0.926	0.782	0.144
1.490	0.687	0.838	0.590	0.248	
27	1.184	1.000	1.109	0.825	0.284
1.641	0.783	0.964	0.631	0.333	
30	1.183	0.993	1.108	0.803	0.305
1.560	0.838	1.008	0.633	0.375	
33	1.351	1.079	1.229	0.802	0.427
1.487	0.926	1.093	0.625	0.468	
36	1.330	1.052	1.208	0.746	0.462
1.507	0.926	1.104	0.650	0.454	
39	1.288	1.027	1.178	0.672	0.506
1.547	0.881	1.044	0.649	0.395	

C D

ON OFF IOP DECAY DELTA ON OFF IOP
DECAY DELTA

Bottom	1.735	0.774	0.866	0.660	0.206

2.089	0.800	0.899	0.665	0.234	
3	1.898	0.750	0.845	0.622	0.223
2.170	0.765	0.869	0.634	0.235	
6	2.012	0.708	0.802	0.590	0.212
2.272	0.724	0.830	0.589	0.241	
9	2.649	0.658	0.764	0.545	0.219
2.424	0.673	0.787	0.552	0.235	
12	2.288	0.616	0.711	0.503	0.208
2.450	0.633	0.743	0.514	0.229	
15	2.133	0.583	0.676	0.472	0.204
2.410	0.596	0.709	0.483	0.226	
18	0.946	0.589	0.749	0.465	0.284
2.521	0.575	0.690	0.465	0.225	
21	2.181	0.571	0.677	0.449	0.228
2.459	0.575	0.689	0.458	0.231	
24	2.469	0.594	0.720	0.460	0.260
2.512	0.582	0.709	0.462	0.247	
27	3.577	0.642	0.786	0.485	0.301
2.662	0.611	0.743	0.474	0.269	
30	2.324	0.689	0.829	0.514	0.315
2.577	0.638	0.779	0.491	0.288	
33	3.465	0.725	0.880	0.543	0.337
2.735	0.666	0.818	0.508	0.310	
36	2.677	0.750	0.911	0.559	0.252
2.742	0.692	0.846	0.521	0.325	
39	2.209	0.770	0.917		2.578
0.702	0.857	0.521	0.336		

CORDELL HULL READINGS
(8/25/39)

E F

ON OFF IOP DECAY DELTA ON OFF IOP
DECAY DELTA

Bottom	2.371	0.824	0.940	0.710	0.230
2.300	0.832	0.940	0.684	0.256	
3	2.463	0.794	0.906	0.651	0.255
2.336	0.786	0.900	0.659	0.241	
6	2.623	0.743	0.868	0.614	0.254
2.504	0.752	0.871	0.621	0.250	
9	3.236	0.699	0.842	0.574	0.268
2.771	0.718	0.849	0.584	0.265	
12	3.265	0.669	0.816	0.539	0.277
2.863	0.688	0.824	0.550	0.274	
15	2.909	0.672	0.815	0.513	0.302
2.838	0.662	0.807	0.527	0.280	
18	4.842	0.655	0.844	0.499	0.345
3.096	0.630	0.779	0.507	0.272	
21	3.202	0.606	0.747	0.485	0.262
3.000	0.619	0.758	0.495	0.263	
24	3.315	0.608	0.753	0.481	0.272
3.055	0.618	0.758	0.488	0.270	
27	5.663	0.641	0.838	0.486	0.352
3.234	0.623	0.770	0.489	0.281	
30	3.225	0.629	0.784	0.490	0.294
3.111	0.627	0.781	0.492	0.289	
33	3.908	0.649	0.832	0.499	0.333
3.244	0.639	0.801	0.496	0.305	
36	3.904	0.659	0.849	0.504	0.345
3.238	0.650	0.817	0.500	0.317	
39	3.063	0.659	0.827	0.505	0.322
3.069	0.648	0.819	0.501	0.318	

G H

ON OFF IOP DECAY DELTA ON OFF IOP
DECAY DELTA

Bottom	2.211	0.832	0.940	0.698	0.242
2.191	0.786	0.911	0.667	0.244	
3	2.335	0.792	0.904	0.662	0.242
2.272	0.767	0.891	0.646	0.245	
6	2.504	0.751	0.880	0.627	0.253
2.458	0.737	0.866	0.615	0.251	
9	3.131	0.712	0.863	0.590	0.273

2.726	0.704	0.838	0.589	0.249	
12	3.073	0.681	0.827	0.561	0.266
2.846	0.673	0.815	0.560	0.255	
15	3.091	0.658	0.809	0.536	0.273
2.894	0.652	0.792	0.535	0.257	
18	9.732	0.643	0.901	0.518	0.383
3.069	0.633	0.780	0.516	0.264	
21	3.295	0.628	0.779	0.505	0.274
3.036	0.624	0.770	0.505	0.265	
24	3.460	0.617	0.782	0.499	0.283
3.080	0.624	0.771	0.499	0.272	
27	4.493	0.622	0.816	0.498	0.318
3.182	0.628	0.777	0.498	0.279	
30	3.278	0.627	0.790	0.498	0.292
3.100	0.634	0.789	0.498	0.291	
33	4.107	0.646	0.830	0.502	0.328
3.233	0.644	0.811	0.502	0.309	
36	3.699	0.646	0.834	0.505	0.329
3.211	0.647	0.821	0.505	0.316	
39	3.144	0.645	0.816	0.504	0.312
3.065	0.654	0.822	0.506	0.316	

CORDELL HULL READINGS
(8/25/89)

	I					J				
	ON	OFF	IOP	DECAY	DELTA	ON	OFF	IOP	DECAY	DELTA
Bottom	2.211	0.788	0.907	0.660	0.247	2.036	0.805	0.913	0.690	0.223
3	2.290	0.766	0.885	0.636	0.249	2.154	0.743	0.859	0.639	0.220
6	2.465	0.732	0.860	0.606	0.254	2.248	0.707	0.823	0.596	0.227
9	2.802	0.701	0.837	0.576	0.261	2.424	0.672	0.791	0.555	0.236
12	2.861	0.671	0.806	0.547	0.259	2.450	0.639	0.760	0.524	0.236
15	2.875	0.647	0.782	0.524	0.258	2.476	0.622	0.738	0.499	0.239
18	3.418	0.635	0.788	0.508	0.280	2.635	0.608	0.743	0.484	0.259
21	2.993	0.628	0.776	0.500	0.276	2.536	0.609	0.743	0.478	0.265
24	3.115	0.626	0.777	0.496	0.281	2.565	0.612	0.747	0.482	0.265
27	3.567	0.626	0.796	0.496	0.300	2.681	0.630	0.768	0.493	0.275
30	3.115	0.640	0.795	0.500	0.295	2.594	0.655	0.798	0.509	0.289
33	3.888	0.658	0.842	0.507	0.335	2.689	0.691	0.839	0.528	0.311
36	3.527	0.666	0.848	0.514	0.334	2.656	0.710	0.868	0.544	0.324
39	2.949	0.667	0.833	0.517	0.316	2.468	0.723	0.878	0.551	0.327

	K					L				
	ON	OFF	IOP	DECAY	DELTA	ON	OFF	IOP	DECAY	DELTA
Bottom	2.075	0.806	0.918	0.666	0.252	1.690	0.785	0.872	0.806	0.066
3	2.026	0.743	0.851	0.639	0.212	1.568	0.750	0.831	0.722	0.109
6	2.066	0.701	0.807	0.606	0.201	1.569	0.739	0.817	0.719	0.098
9	2.359	0.666	0.774	0.563	0.211	1.660	0.721	0.801	0.719	0.082

12	2.363	0.635	0.737	0.528	0.209
1.617	0.719	0.793	0.712	0.081	
15	2.294	0.606	0.716	0.500	0.216
1.520	0.712	0.784	0.720	0.064	
18	3.036	0.602	0.731	0.481	0.250
1.728	0.687	0.775	0.716	0.059	
21	2.344	0.602	0.728	0.479	0.249
1.419	0.740	0.862	0.625	0.237	
24	2.486	0.628	0.762	0.487	0.275
1.372	0.792	0.952	0.869	0.083	
27	3.315	0.673	0.828	0.525	0.303
1.752	0.797	0.945	0.872	0.073	
30	2.370	0.697	0.839	0.534	0.305
1.680	0.820	0.964	0.863	0.101	
33	3.200	0.739	0.917	0.562	0.355
1.680	0.907	1.061	0.839	0.222	
36	2.695	0.765	0.932	0.575	0.357
1.672	0.929	1.098	0.793	0.305	
39	2.195	0.775	0.927	0.588	0.339
1.599	0.894	1.042	0.717	0.325	

M

ON	OFF	IOP	DECAY	DELTA	
Bottom	1.273	0.888	0.937	0.701	0.236
3	1.312	0.832	0.899	0.673	0.226
6	1.301	0.840	0.909	0.652	0.257
9	1.243	0.844	0.906	0.636	0.270
12	0.993	0.820	0.877	0.607	0.270
15	1.027	0.872	0.955	0.583	0.372
18	1.032	0.859	0.950	0.542	0.408
21	0.901	0.796	0.850	0.541	0.309
24	1.038	0.907	0.986	0.572	0.414
27	1.115	0.971	1.052	0.586	0.466
30	1.137	0.982	1.073	0.619	0.454
33	1.297	1.072	1.189	0.647	0.542
36	1.308	0.988	1.129	0.660	0.469
39	1.351	0.920	1.049	0.659	0.390

APPENDIX D:

NATIVE POTENTIALS FOR CORDELL HULL DAM, NORTH TAINTER GATE*

CORDELL HULL LOCK AND **DAM TAINTER GATE**
NORTH GATE NATIVE POTENTIAL DATA
4/20/88

(See Drawing for South Gate for Data Locations)

	A	C	E	G	I	K	M
Surface	0.402	0.362	0.279	0.262	0.278	0.346	0.381
3	0.466	0.342	0.276	0.260	0.273	0.342	0.511
6	0.481	0.353	0.270	0.258	0.266	0.332	0.526
9	0.462	0.333	0.262	0.255	0.259	0.315	0.527
12	0.460	0.301	0.255	0.251	0.251	0.290	0.515
15	0.300	0.259	0.249	0.249	0.244	0.255	0.393
18	0.265	0.232	0.244	0.247	0.238	0.228	0.261
21	0.244	0.223	0.242	0.249	0.237	0.216	0.195
24	0.254	0.227	0.243	0.252	0.269	0.218	0.202
27	0.258	0.239	0.247	0.255	0.244	0.228	0.229
30	0.271	0.253	0.253	0.257	0.249	0.241	0.247
33	0.283	0.268	0.258	0.259	0.254	0.254	0.261
36	0.289	0.275	0.261	0.259	0.256	0.261	0.269
37	0.291	0.275	0.261	0.259	0.257	0.261	0.271

*Before the magnesium strip anodes were added between the chain and the wall in 1989

APPENDIX E:

DEPOLARIZATION DECAY CHART FOR CORDELL HULL DAM

CORDELL HULL

DEPOLARIZATION DECAY CHART
(8/25/89)

TIME	POTENTIAL
IOP*	0.778
OFF**	0.633
0:00:08	0.600
0:00:25	0.585
0:00:30	0.582
0:00:45	0.577
0:00:60	0.574
0:01:30	0.569
0:02:00	0.565
0:02:30	0.563
0:03:00	0.561
0:04:00	0.557
0:05:00	0.555
0:06:00	0.553
0:07:00	0.551
0:08:00	0.550
0:09:00	0.549
0:10:00	0.549
0:17:00	0.541
0:30:00	0.534
4:57:00	0.530
5:12:00	0.524
5:52:00	0.517
6:12:00	0.516

* IOP = Instant Off Potential as measured with Xetron and verified with Leader LCD-100 Scope

** OFF = Off Potential measured with 2nd Fluke Model 75 DVM Update

APPENDIX F:

CERANODE LSA EQUIPOTENTIAL DATA ON POTENTIALS VERSUS SAFE OFF POTENTIALS CLOSE TO ANODE AT CORDELL HULL DAM

DETAILED EQUIPOTENTIAL BETWEEN ANODES #12 AND #13

According to the 1988 off potential data below, the polarization potential next to the LSA does not reach any value of concern from hydrogen production and paint damage. This remains true even if an additional 140 mV is added to the off potential readings as the instant off potential readings suggest should be done in some cases. See main body of data.

CENTER (#3) POSITION

EQUIPOTENTIAL AT CENTER OF GATE

DISTANCE NO.*	ON POTENTIAL	OFF POTENTIAL
At Anode Center #13	18.20	0.88
2 In.	16.90	0.89
4 In.	10.54	0.76
6 In.	8.08	0.73
8 In.	7.03	0.72
10 In.	6.51	0.71
12 In.	6.12	0.72
2 Ft.	4.98	0.70
3 Ft.	4.61	0.70
4 Ft.	4.48	0.70
5 Ft.	4.51	0.69
6 Ft.	4.91	0.69
7 Ft.	6.71	0.69
7 Ft. 2 In.	7.84	0.70
7 Ft. 4 In.	9.59	0.70
At Anode Center #12	12.48	0.71

* Distance away from center of Anode #13 moving up to Anode #12

APPENDIX G:

CERANODE DATA ON CORDELL HULL RECTIFIER

CORDELL HULL

RECTIFIER READINGS

CIRCUIT #2	CIRCUIT #1	CIRCUIT #3
18.74 Volts	20.42 Volts	20.77 Volts
0.36 Amperes	0.64 Amperes	0.94 Amperes
6.7 Watts	13.1 Watts	19.5 Watts

JUNCTION BOX READINGS
(8/25/89)

CIRCUIT #2		CIRCUIT #1		CIRCUIT #3	
ANODE NO.	CURRENT	ANODE NO.	CURRENT	ANODE NO.	CURRENT
5	0.072	1	0.080	6	0.080
10	0.072	2	0.074	7	0.073
15	0.065	3	0.072	8	0.072
20	0.069	4	0.075	9	0.074
25	0.068	21	0.078	11	0.078
		22	0.076	12	0.074
		23	0.000	13	0.073
		24	0.082	14	0.074
		26	0.078	16	0.078
				17	0.074
				18	0.073
				19	0.074

Total Power Rectifier = 7.7 + 13.1 + 15.9 = 39.3 Watts

APPENDIX H:

CERANODE POTENTIAL SURVEY DATA FOR CAPE CANAVERAL

CAPE CANAVERAL READINGS
(8/29/89)

GATE NO. 1

A B C

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.837 0.820 0.660 0.160 0.851
0.816 0.666 0.150 0.901 0.885 0.653 0.232
Middle 0.870 0.833 0.670 0.163 0.873
0.819 0.672 0.147 0.939 0.892 0.660 0.232
Top 0.868 0.832 0.669 0.163 0.875 0.820
0.672 0.148 0.939 0.897 0.663 0.234

D E F

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.851 0.844 0.672 0.172 0.853
0.838 0.684 0.154 0.839 0.827 0.664 0.163
Middle 0.856 0.848 0.672 0.176 0.861
0.848 0.687 0.161 0.846 0.833 0.665 0.168
Top 0.860 0.852 0.672 0.180 0.861 0.850
0.688 0.162 0.845 0.838 0.665 0.173

G H I

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.845 0.832 0.668 0.164 0.840
0.832 0.673 0.159 0.831 0.826 0.674 0.152
Middle 0.847 0.832 0.668 0.164 0.843
0.834 0.672 0.162 0.833 0.825 0.673 0.152
Top 0.846 0.833 0.668 0.165 0.841 0.834
0.670 0.164 0.831 0.825 0.673 0.152

All Cape Canaveral data was measured with a permanent type Ag/AgCl **reference cell which is 71 mV lower than a permanent type** Cu/CuSo4 reference cell.

CAPE CANAVERAL READINGS
(8/29/89)

GATE NO. 2

A B C

DEPTH	ON	IOP	DECAY	SHIFT	ON	IOP
DECAY	SHIFT	ON	IOP	DECAY	SHIFT	
Bottom	0.817	0.800	0.692	0.108	0.831	
0.810	0.697	0.113	0.863	0.854	0.688	0.166
Middle	0.826	0.809	0.694	0.115	0.845	
0.807	0.697	0.110	0.880	0.856	0.693	0.163
Top 0.822	0.806	0.693	0.113	0.841	0.807	
0.697	0.110	0.875	0.862	0.690	0.172	

D E F

DEPTH	ON	IOP	DECAY	SHIFT	ON	IOP
DECAY	SHIFT	ON	IOP	DECAY	SHIFT	
Bottom	0.813	0.809	0.695	0.114	0.817	
0.810	0.688	0.122	0.820	0.810	0.689	0.121
Middle	0.822	0.815	0.695	0.120	0.824	
0.815	0.691	0.124	0.824	0.815	0.690	0.125
Top 0.818	0.813	0.695	0.118	0.825	0.818	
0.691	0.127	0.822	0.815	0.690	0.125	

G H I

DEPTH	ON	IOP	DECAY	SHIFT	ON	IOP
DECAY	SHIFT	ON	IOP	DECAY	SHIFT	
Bottom	0.819	0.809	0.694	0.115	0.811	
0.803	0.696	0.107	0.806	0.800	0.695	0.105
Middle	0.820	0.809	0.694	0.115	0.814	
0.807	0.695	0.112	0.806	0.799	0.694	0.105
Top 0.820	0.809	0.694	0.115	0.812	0.807	
0.694	0.113	0.805	0.798	0.694	0.104	

All Cape Canaveral data was measured with a permanent type Ag/AgCl reference cell which is 71 mV lower than a permanent type Cu/CuSo4 reference cell.

CAPE CANAVERAL READINGS
(8/29/89)

GATE NO. 3

A B C

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.870 0.850 0.670 0.180 0.890
0.871 0.663 0.208 0.901 0.885 0.653 0.232
Middle 0.884 0.856 0.675 0.181 0.909
0.854 0.670 0.184 0.939 0.892 0.660 0.232
Top 0.879 0.851 0.676 0.175 0.905 0.851
0.671 0.180 0.939 0.897 0.663 0.234

D E F

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.856 0.850 0.677 0.173 0.876
0.867 0.679 0.188 0.865 0.856 0.680 0.176
Middle 0.862 0.856 0.677 0.179 0.881
0.868 0.679 0.189 0.870 0.860 0.681 0.179
Top 0.862 0.856 0.677 0.179 0.881 0.868
0.679 0.189 0.870 0.862 0.681 0.181

G H I

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.868 0.854 0.682 0.172 0.855
0.849 0.684 0.165 0.841 0.836 0.684 0.152
Middle 0.866 0.853 0.682 0.171 0.856
0.850 0.684 0.166 0.844 0.836 0.683 0.153
Top 0.866 0.854 0.682 0.172 0.885 0.850
0.683 0.167 0.844 0.838 0.683 0.155

All Cape Canaveral data was measured with a permanent type Ag/AgCl reference cell which is 71 mV lower than a permanent type Cu/CuSo4 reference cell.

CAPE CANAVERAL READINGS
(8/29/89)

GATE NO. 4

A B C

DEPTH	ON	IOP	DECAY	SHIFT	ON	IOP
DECAY	SHIFT	ON	IOP	DECAY	SHIFT	
Bottom	0.805	0.790	0.689	0.101	0.826	
0.815	0.696	0.119	0.863	0.854	0.688	0.166
Middle	0.821	0.798	0.697	0.101	0.841	
0.802	0.699	0.103	0.880	0.856	0.693	0.163
Top	0.824	0.808	0.696	0.112	0.846	0.801
0.699	0.102	0.875	0.862	0.690	0.172	

D E F

DEPTH	ON	IOP	DECAY	SHIFT	ON	IOP
DECAY	SHIFT	ON	IOP	DECAY	SHIFT	
Bottom	0.812	0.809	0.699	0.110	0.824	
0.820	0.697	0.123	0.821	0.814	0.698	0.116
Middle	0.817	0.813	0.698	0.115	0.830	
0.821	0.698	0.123	0.826	0.819	0.697	0.122
Top	0.816	0.813	0.698	0.115	0.829	0.821
0.698	0.123	0.825	0.817	0.697	0.120	

G H I

DEPTH	ON	IOP	DECAY	SHIFT	ON	IOP
DECAY	SHIFT	ON	IOP	DECAY	SHIFT	
Bottom	0.825	0.811	0.698	0.113	0.811	
0.807	0.700	0.107	0.806	0.803	0.698	0.105
Middle	0.825	0.814	0.698	0.116	0.814	
0.809	0.698	0.111	0.809	0.803	0.698	0.105
Top	0.825	0.814	0.698	0.116	0.811	0.809
0.697	0.112	0.809	0.803	0.697	0.106	

All Cape Canaveral data was measured with a permanent type Ag/AgCl reference cell which is 71 mV lower than a permanent type Cu/CuSo4 reference cell.

APPENDIX I:

CERANODE DATA ON CANAVERAL RECTIFIERS

CAPE CANAVERAL RECTIFIERS

GATE NO. I

Manufacturer: Universal - 8 Circuits

Model: ASP-CC

Type: Constant Current

Serial Numbers: 860791

Primary: 120 VAC, 10 Amperes, Single Phase, 60 Hz, 45oC

Output: 24 Volts/Circuit, 4 Amperes/Circuit

OPERATING DATA (8/29/89)

Circuit No.	Shunt Meter	Amperes Volts	Amperes 1mV(10 mV = 1 Amperes)	Calculated
1	3.88	24.08	2.40	2.5
2	3.95	19.37	1.94	2.0
3	3.66	7.44	0.74	0.7
4	3.82	7.38	0.74	0.7
5	3.75	7.36	0.74	0.7
6	3.44	7.47	0.75	0.7
7	3.36	7.35	0.74	0.7
8	3.75	21.33	2.13	2.2

CAPE CANAVERAL RECTIFIERS

GATE NO. III

Manufacturer: Universal - 8 Circuits

Model: ASP-CC

Type: Constant Current

Serial Numbers: 860789

Primary: 120 VAC, 10 Amperes, Single Phase, 60 Hz, 45oC

Output: 24 Volts/Circuit, 4 Amperes/Circuit

OPERATING DATA (8/29/89)

Shunt Circuit No. Meter	Amperes Volts	Amperes 1mV(10 mV = 1 Amperes)	Calculated	
1	4.04	25.22	2.52	2.5
2	3.94	20.51	2.05	2.0
3	3.66	7.58	0.76	0.7
4	3.62	7.66	0.77	0.7
5	3.56	7.68	0.77	0.7
6	3.47	7.57	0.76	0.7
7	3.42	7.54	0.75	0.7
8	4.02	22.19	2.22	2.2

CAPE CANAVERAL RECTIFIERS

GATE NO. II

Manufacturer: Universal - 8 Circuits

Model: ASP-CC

Type: Constant Current

Serial Numbers: 860790

Primary: 120 VAC, 10 Amperes, Single Phase, 60 Hz, 45oC

Output: 24 Volts/Circuit, 4 Amperes/Circuit

OPERATING DATA (8/29/89)

Circuit No.	Shunt Meter	Amperes Volts	Amperes 1mV(10 mV = 1 Amperes)	Calculated
1	3.27	17.57	1.76	1.7
2	3.19	12.54	1.25	1.2
3	2.91	3.42	0.34	0.3
4	2.92	3.36	0.34	0.3
5	3.60	5.57	0.56	0.5
6	3.05	5.47	0.55	0.5
7	2.92	5.44	0.54	0.5
8	3.20	16.64	1.66	1.6

CAPE CANAVERAL RECTIFIERS

GATE NO. IV

Manufacturer: Universal - 8 Circuits

Model: ASP-CC

Type: Constant Current

Serial Numbers: 860792

Primary: 120 VAC, 10 Amperes, Single Phase, 60 Hz, 45oC

Output: 24 Volts/Circuit, 4 Amperes/Circuit

OPERATING DATA (8/29/89)

Shunt Circuit No. Meter		Amperes Volts	Amperes 1mV(10 mV = 1 Amperes)	Calculated
1	3.31	17.33	1.73	1.7
2	3.25	12.64	1.26	1.2
3	3.19	3.69	0.37	0.3
4	3.03	3.53	0.35	0.3
5	3.24	5.99	0.60	0.5
6	3.04	5.86	0.59	0.5
7	2.91	5.80	0.58	0.5
8	3.34	16.59	1.66	1.6

APPENDIX J:

PREADJUSTMENT POTENTIAL STATUS, GATE NO. 2, TYPICAL OF ALL FOUR GATES

CAPE CANAVERAL READINGS
(8/29/89)

GATE NO. 2

(PRE-ADJUSTMENT POTENTIAL STATUS)

A B C

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.693 0.686 0.692 -0.006 0.710
0.704 0.697 0.069 0.692 0.686 0.688
-0.002
Middle 0.713 0.704 0.694 0.010 0.715
0.704 0.697 0.007 0.709 0.704 0.693 0.011
Top 0.698 0.692 0.693 0.001 0.710 0.701
0.697 0.004 0.708 0.702 0.690 0.012

D E F

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.709 0.705 0.695 0.010 0.711
0.705 0.688 0.017 0.712 0.708 0.689 0.019
Middle 0.711 0.707 0.695 0.012 0.714
0.710 0.691 0.019 0.713 0.709 0.690 0.019
Top 0.711 0.708 0.695 0.013 0.713 0.710
0.691 0.019 0.712 0.709 0.690 0.019

G H I

DEPTH ON IOP DECAY SHIFT ON IOP
DECAY SHIFT ON IOP DECAY SHIFT

Bottom 0.712 0.707 0.694 0.013 0.711
0.706 0.696 0.010 0.708 0.704 0.695 0.009
Middle 0.713 0.707 0.694 0.013 0.711
0.708 0.695 0.013 0.710 0.705 0.694 0.011
Top 0.713 0.707 0.694 0.013 0.710 0.705
0.694 0.011 0.710 0.705 0.694 0.011

All Cape Canaveral data was measured with a permanent type Ag/AgCl reference cell which is 71 mV lower than a permanent type Cu/CuSo4 reference cell.

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